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5 GEOLOGY

The information in Chapter 5 is presented to comply with regulatory requirements that specify the minimum geologic criteria for siting hazardous waste injection wells and that also require the geologic system be sufficiently characterized to demonstrate containment. In response to these requirements, this section includes a detailed analysis of regional geology, stratigraphy, and hydrology for the P&U Kalamazoo site and local area. State-wide and county/township-specific geologic data were used to characterize regional and local geology, stratigraphy, and hydrology to meet these regulatory requirements.

As indicated by the successful use of over a thousand permitted Class II and Class I injection wells in the state of Michigan, the geologic setting of the state can be ideally suited for deepwell injection in selected formations. Many of the stratigraphic units within Michigan are laterally persistent and can be traced from outcrop into the subsurface across the Michigan Basin. Stratigraphic units include interbedded sandstones, shales, and carbonates of different porosities and permeabilities, with several of these comprised of low permeability shales and shaley carbonates that form hundreds of feet of hydraulic barriers.

Regulations define the Injection Zone as a geological formation, group of formations, or a part of a formation, that accept fluid through a well, and includes both the strata directly receiving the fluids (Injection Interval) and portions of the overlying, less permeable layers where fluid will be contained over 10,000 years (Arrestment Interval). The Confining Zones both overlie and underlie the Injection Zone, and the overlying Confining Zone provides further assurance that fluids will not be able to migrate from the Injection Zone into a USDW.

At the P&U Kalamazoo, Michigan site (Figure 1-1), the permit and petition-specified Injection Zone is the interval from the top of the Franconia/base of Trempealeau to the Precambrian basement. The Mt. Simon Formation and lower portion of the Eau Claire (e.g. 4,750 feet to TD in both wells) comprise the Injection Interval, while the Franconia, Galesville/Dresbach, and Upper Eau Claire (e.g. 4,254 – 4,750 feet RKB at Well No 4) constitute the Arrestment Interval. The Injection Interval is approximately 850 feet thick and the Arrestment Interval is approximately 500 feet thick. The Arrestment Interval is both a physical and hydrostatic barrier to upward flow out of the Injection Interval.

The Trempealeau Formation (3,992-4,254 feet RKB at Well No. 4) is the Upper Confining Zone and Precambrian basement is the Lower Confining Zone at the P&U site. The Trempealeau Formation is composed of approximately 250 feet of low permeability rock that provides an additional margin of safety for injectate containment above the Arrestment Interval. Approximately 3,600 feet of rock is present between the top of the Confining Zone and the base of the lowermost USDW at the site. This interval consists of various shales, evaporites, carbonates, and sandstone units ranging from Silurian to Mississippian in age. See Figure 1-1 for a graphical display of both the regulatory and geologic units at the Site.

The Mt. Simon-Lower Eau Claire in southwestern Michigan has a naturally occurring total dissolved solids (natural TDS) concentration that is often in excess of 150,000 ppm and a history of use for Class I injection. Regional and local geology verify both the lateral continuity of the Injection Zone and Confining Zones, and data at least show no evidence of larger-scale faults through the Injection Zone or Confining Zone within 20 miles of the P&U facility.

5.1 REGULATORY STANDARD

Chapter 5 addresses all geologic and hydrologic data necessary to meet the regulatory requirements that "…the geology of the area can be described confidently." The standards are:

Part 146 - Underground Injection Control Program: Criteria and Standards, Subpart G - Criteria and Standards Applicable to Class I Hazardous Waste Injection Wells *40 CFR §* 146.62 specifies the minimum geologic criteria for siting of hazardous waste injection wells.

Further, *40 CFR §* 148.21(b) requires that certain site-specific geologic information be provided in the petition. Geologic suitability of the site is presented in Sections 5.2, 5.3 and 5.4 below, and addresses:

> "*40 CFR §* 148.21(b) Any petitioner shall provide sufficient site-specific information to support the demonstration such that:
>
> (1) Thickness, porosity, permeability, and extent of the various strata in the Injection Zone;
>
> (2) Thickness, porosity, permeability, extent, and continuity of the Confining Zone;

(3) Hydraulic gradient in the Injection Zone;
(4) Hydrostatic pressure in the Injection Zone…"

And:

"*40 CFR §* 146.62(b) The siting of Class I hazardous waste wells shall be limited to areas that are geologically suitable. The Director shall determine the geologic suitability based upon:

(1) An analysis of the structural and stratigraphic geology, hydrogeology, and the seismicity of the region.
(2) An analysis of the local geology and hydrogeology of the wellsite including at a minimum detailed information regarding stratigraphy, structure and rock properties, aquifer hydrodynamics and mineral resources.
(3) A determination that the geology of the area can be described confidently and that waste fate and transport can be accurately modeled."

In addition to the above, Section 5.5 of this Petition demonstrates the suitability of both the injection and Confining Zone as required:

"*40 CFR §* 146.62(c) Class I hazardous waste injection wells shall be sited in such a manner that:

(1) The Injection Zone has sufficient permeability, porosity, thickness and areal extent to prevent migration of fluids into USDWs.
(2) The Confining Zone:
   (i) Is laterally continuous and free of transecting transmissive faults or fractures over an area sufficient to prevent the movement of fluids into a USDW
   (ii) Contains at least one formation of sufficient thickness and with lithologic characteristics capable of preventing vertical propagation of fractures."

And:

"(d) The owner or operator shall demonstrate to the satisfaction of the Director that:

(1) the Confining Zone is separated from the base of the lowermost USDW by at least one sequence of permeable and less permeable strata that provide an added layer of protection for the USDW in the event of fluid movement in an unlocated borehole or transmissive fault

-or-

(2) Within the Area of Review the piezometric surface of the fluid in the Injection Zone is less than the piezometric surface of the lowermost USDW considering density effects, injection pressures and any significant pumping in the overlying USDW

-or-

(3) There is no USDW present
(4) The Director may approve a site which does not meet the requirements in paragraph (d) (1), (2) or (3) section if the owner or operator can demonstrate to the Director that because of the geology, nature of the waste, or other

considerations, abandoned boreholes or other conduits would not cause endangerment of USDWs."

The Injection Zone and Confining Zone are defined as follows:

- The Injection Zone is defined as the zone from the top of the Franconia (depth of 4,254 feet RKB in P&U Well No. 4) into the top of the Precambrian Granite (approximately 5,600 feet RKB at Well No. 4). The Injection Zone includes both the Injection Interval (Mt. Simon-Lower Eau Claire, top of which is defined as 4,750 feet RKB) and the Arrestment Interval (top of Lower Eau Claire to the top of the Franconia, i.e. 4,254 to 4,750 feet RKB in Well No. 4). Figure 1-1 for specific depths of the Arrestment and Injection Intervals at each well.

- The Confining Zone is defined as the Trempealeau formation, which occurs from 3,992 to 4,254 feet at Well No. 4. See Figure 1-1 for the specific depths of the Confining Zone at each well.

5.2 REGIONAL GEOLOGIC ANALYSIS

5.2.1 General History of the Michigan Basin

The Michigan Basin is an intracratonic basin that occupies an area of about 80,000mi^2 (Catacosinos et al. 1991) (Figure 5.2-1a). The basin is nearly circular and was created by four different styles of subsidence: trough-shaped, regional tilting, narrow basin-centered and broad basin-centered (Howell and van der Pluijm, 1999). The basin is centered on Michigan's southern peninsula and is generally separated from other nearby basins by major arches. The basin is characterized structurally by several Paleozoic anticlines that trend northwest-southeast, which some authors (e.g. Wood and Harrison, 2002) present in association with basement faults or lineaments.

The Michigan Basin contains as much as 16,000 feet of sedimentary rock, covered by up to 1,200 feet of Pleistocene-age glacial drift (Catacosinos et al. 1991). Figure 5.2-1b is a Geologic Map of Michigan, showing the subcrop configuration of strata in the Michigan Basin. The

Precambrian basement underlying the Michigan Basin is part of the Superior Province, and is approximately 1.2 to 1.5 billion years old. About 5,000 feet of thickened Precambrian-age sedimentary rock occurs above basement along a north-south trending linear trend associated with a gravity anomaly that has been interpreted by Catacosinos, et al. (1991) and others to be a portion of a buried ancient rift system (Figure 5.2-2). Adjacent to this trend, Cambrian rocks occur above the crystalline Precambrian basement, as is the case at the P&U site (referred to hereafter as the Site). The Cambrian Period included times when large land areas were present throughout what is now the central United States, composed of granite or metamorphic rocks and sedimentary rocks that served as a source of sediments for overlying Cambrian units. Depositional settings of stratigraphic units within the basin were controlled by sea-level fluctuations (Catacosinos et al. 1991). In the Early Cambrian, near shore sediments were deposited along irregular coastlines, represented by the Jacobsville and other Pre-Mt. Simon clastic units. Expert opinion is inclusive as to whether these older units are present in southwestern Michigan.

A gradual marine transgression occurred through the Late Cambrian. Late Cambrian deposits including the Mt. Simon, Eau Claire, Galesville/Dresbach, and Franconia are probably marine in origin, with the source of sedimentary material originating from northeast. By the end of the Cambrian Period, most of the United States was under water. This circumstance continued through the Ordovician in the Michigan Basin area. Cambrian-Lower Ordovician units were deposited within a northerly transgressing epicontinental sea; the units are predominantly siliciclastic and can be over 4,500 feet thick in the center of the basin.

The Lower Ordovician Trempealeau Formation and Prairie du Chien Group were also generally deposited in a marine environment. A minor regression preceded the deposition of the onshore/near shore St. Peter Sandstone. Deposition of the offshore marine shale and carbonates of the Trenton and Black River Formations was followed by another regression, with an accompanying unconformity. The late Ordovician Richmond Group, which includes the Utica Shale, is composed of shale deposited in a deep water environment.

During the Silurian, the Michigan Basin was an interior sea surrounded by low lying land areas that partially isolated the sea from other bodies of water. In the absence of a significant nearby source of clastic material, the main deposits of the Silurian were evaporite and reef deposits.

The Middle Silurian Niagara Formation was deposited throughout the lower peninsula of Michigan, and is composed of carbonate reef deposits. Progressive isolation of the Basin with respect to water influx is evidenced by deposition of the Salina Formation, which contains evaporates including anhydrite and halite that were deposited in the relatively restricted inland sea. During the Silurian, over 3,000 feet of sediment was deposited in the center of the Michigan Basin.

The base of the Devonian Period is represented by an unconformity as the seas regressed and land emerged, which was followed by transgression and subsequent deposition of carbonate-rich sequences through the early and middle Devonian. The Devonian Detroit River Group consists of carbonates and evaporites, with some shale. The Dundee Formation, which consists of carbonates, was deposited after the Detroit River Group. During the Late Devonian, uplift in the Appalachian Region to the east provided a siliciclastic sediment source and subsequent deposition of shale-rich sequences including the shale of the Antrim Formation, Ellsworth Formations and Mississippian Coldwater Formations.

Devonian rocks are capped by the deposition of predominantly siliciclastic units during the Mississippian and Pennsylvanian periods. Depositional environments found during this time period include marine, coastal, and terrestrial environments, and represent a return to continental systems. Terrigenous Jurassic “Red Beds” are present in the center of the Basin (Catacosinos, et. al, 1991).

5.2.2 Regional Structural Geology

The Site at Kalamazoo is located on the southwestern flank of the Michigan Basin shown in Figure 5.2-1a. The Michigan Basin resulted from epeirogenic downwarping during the Paleozoic Era, and subsidence of the basin controlled the deposition of sedimentary units during the Paleozoic. Each Paleozoic unit dips toward the center of the basin, and also generally thickens basinward. The basin extends into northwest Ohio and northeast Indiana and covers all of the Lower Peninsula of Michigan. The structural axis of the Findlay Arch is southeast of the Basin and the axis of the Kankakee Arch is to the southwest. Regional dip in the Site vicinity is to the northeast at 40-60 feet per mile.

Catacosinos et al. (1991) states that at least “three structural platforms” were present in the Michigan Basin that differentially affected isopach and facies relationships within stratigraphic units. These platforms were located in the southeastern, northeastern, and southwestern portions of the Basin. Structural features present in the Basin were characterized by northwest-southeast trending features that Catacosinos indicates some authors believe are the result of vertical tectonics, possibly anticlines and/or horst and graben sequences. Catacosinos states that “almost all the faulting in the Precambrian tends to die out upwards and that only a few of the largest faults extend through the Middle Devonian Section. Faulting across the Mississippian-Pennsylvanian unconformity has not yet been reported.”

According to Catacosinos et al. (1991), during Late Precambrian time rifting occurred across the midcontinent, as evidenced by a rift zone in Michigan Basin basement rocks (Figure 5.2-2). Rifting was followed by thermal subsidence creating a “sag basin” in the late Cambrian. Basin subsidence began during the early Ordovician with concurrent deposition of thick stratigraphic sequences. The current northwest-southeast structural grain apparent in regional structural maps (e.g. Figure 5.2-3) was imposed in late Mississippian to Pennsylvanian “possibly as the result of flexural foreland subsidence in response to the Alleghenian-Hercynian Orogeny…” (Catacosinos et al. 1991).

Milstein (1989) states that the distribution of Cambrian strata indicates “successively younger beds overlap to lie directly on the Precambrian…This suggests that the regional configuration of the Precambrian surface, during Cambrian times, was similar to its present shape”. Milstein (1989) also suggests that isopachous variations in overlying Cambrian units reflect irregularities on the Precambrian surface: “prominent Precambrian features like the Washtenawa Anticlinorium in southeastern Michigan, and the Bowling Green Fault located along the Leawee and Monroe County boundary, are both reflected in the Cambrian sediments.”

Wood and Harrison (2002) explored the occurrence and expression of faults within the Michigan Basin through mapping of post-Silurian sediments. They concluded that the “Michigan Basin is cut by numerous (12+) major faults lying below the glacial drift and below the topmost Jurassic sediments”. The lineations generally trend northwest-southeast (Figure 5.2-3). These lineations are dominant features of the subsurface topography and are well documented, occurring as structural features expressed in units from at least the Late Devonian (Dundee time) to the Mississippian. Wood and Harrison state "These faults carve out [a] large depression in the Central Michigan Basin and appear to be responsible for shallow anticlines that hold or held a significant portion of the hydrocarbons in the Michigan Basin". The origin of these faults was attributed to deep-seated normal basement faults "rooted in the Precambrian rift sequence". Figure 5.2-3 presents the location of these northwest-southeast trending features presumably associated with basement faults, and Figure 5.2-2 presents the mapped location of the basement rift system. No faults are projected to be within miles of the Site, with the closest identified major fault at least 50-75 miles east and northeast of the Site, well outside the AOR or local structural maps prepared for this study.

5.2.3 Regional Stratigraphy

Figure 5.2-4 presents the stratigraphic column for Michigan. Figures 5.2-5 and 5.2-6 are regional cross sections available from the literature, and show regional stratigraphic continuity and geologic structure across the southwestern portion of the Michigan Basin.

5.2.3.1 Precambrian (Lower Confining Zone)

The Precambrian crystalline basement is described as primarily metasedimentary gneiss (mafic and felsic) formed by the metamorphism of igneous rock as well as shales, sandstones, carbonate and iron formations. Igneous intrusions may also occur within these units. The Precambrian basement is estimated to occur at about 5,617-5,600 feet RKB (-4,732 to -4,726 subsea) at the Site (Figure 5.2-7), and serves as the lower Confining Zone. In southwest Michigan near the Site, the Precambrian dips at approximately 50-55 feet per mile to the northeast, toward the center of the Michigan Basin, and may occur at least 14,000 feet or more below ground surface near the basin center.

5.2.3.2 Cambrian Systems (Injection Zone, Including the Injection Interval, Arrestment Interval, and Confining Zone)

The Cambrian is composed of the Munising Group that includes the Mount Simon Sandstone, Eau Claire Formation, Galesville/Dresbach Sandstone, and the Franconia Formation as well as the overlying Trempealeau Formation. The Cambrian Munising is the Injection Zone, which is composed of the Injection Interval (Mt. Simon-Lower Eau Claire defined by permit and petition as -4,750 RKB) and Arrestment Interval (-4,750 RKB to the top of the Franconia/base of Trempealeau).

Units from the Franconia to the top of the Mt. Simon comprise the Munising Group, although various authors have also included the Mt. Simon in the Munising Group. For the purposes of this report, the Munising Formation is assumed to consist of the Mt. Simon, Eau Claire, Galesville/Dresbach, and Franconia Formations.

Mt. Simon Sandstone

The Mt. Simon Sandstone (Mt. Simon) is a massive sandstone that is present in the subsurface throughout much of Ohio, Indiana, Illinois, and the lower peninsula of Michigan. Figure 5.2-8a is an isopach of the Mt. Simon, and Figure 5.2-8b is a structure contour map constructed at the top of the Mt. Simon. The Mt. Simon is thickest within the central portions of the Basin, and reaches a thickness of approximately 1,240 feet in the Gratiot County region. The Mt. Simon thins dramatically to the east side of the state, but thickens again in the southwestern portion of the State in Berrien County toward the Illinois Basin.

In the southern peninsula of Michigan, the Mt. Simon typically lies unconformably above the Precambrian Crystalline Basement Complex and occurs about 5,600 feet below ground surface in the Site area. Western Michigan University (WMU) (1981) indicates that the Mt. Simon varies in thickness from 100 feet to over 1,000 feet thick in the lower Peninsula of Michigan, (Figure 5.2-8a), and also subcrops with the Munising Group in the Upper Peninsula. The Mt. Simon is likely more than 650 feet thick in the Kalamazoo area.

The Mt. Simon is described as a subrounded to rounded quartzitic sandstone that is generally fine to coarse grained and well sorted. It is pink to red, with a greater abundance of feldspar at the base of the unit. WMU (1981) states that “glauconite, anhydrite, and green shale are present in minor amounts with local dolomite cement”. Barnes et al. (2009) indicate that the Mt. Simon is composed of three basic units: a basal, arkosic unit, a middle quartz arenite-glauconite unit, and an upper shale-rich unit that grades conformably into the Eau Claire Formation. Some authors and wellsite geologists may have attributed basal pre-Mt. Simon sediments to be part of the basal arkosic Mt. Simon unit.

Regional porosity development is generally related to the burial depth, with better porosity developed in areas with less overburden (Barnes et al. 2009). See Section 5.3.2 for site-specific information pertaining to Mt. Simon properties. State-wide, literature has generally indicated that Mt. Simon porosity typically ranges from 4-20% and may also vary laterally where sandstones grade into more shale or carbonate-rich facies.

The Mt. Simon is a common target for fluid injection, and is under scrutiny as a potential target for CO_2 sequestration. WMU (1981) states that with respect to the Mt. Simon as a whole, regionally "the permeable Cambrian quartz sandstone, siltstone, and arenaceous dolomite suitable for fluid injection comprise about 27% of the stratigraphic column". Barnes et al. (2009) conclude that "The Mount Simon Sandstone in Michigan is an important saline reservoir target for geological sequestration of CO_2 in Michigan". Various authors have concluded that the Mt. Simon has both the capacity to accept injectate and has "cap rocks" suitable to arrest vertical fluid migration.

Eau Claire Formation

The Eau Claire Formation (Eau Claire) occurs conformably above the Mt. Simon in the southern peninsula of Michigan, and consists of interbedded sandstones, siltstones, and shales. It may also include thinly bedded dolomites (Milstein, 1989). It is described as appearing similar to the Mt. Simon, particularly in lower portions where the two units are conformable and the contact is therefore somewhat gradational. In the center of the Michigan Basin, the Eau Claire is composed of up to 100% shale and dense siltstone (UIPC, 1989), with the proportion of shale in the formation decreased toward the basin margins. In the Kalamazoo area, the Eau Clare is relatively shale-rich.

The thickness of the Eau Claire varies considerably within the Michigan Basin. WMU (1981) states that the Eau Claire ranges from 0-1,500 feet thick in the Michigan Basin, with the thickest deposits occurring in the central portion of the Basin. Milstein (1989) believes there to be about 800 feet of Eau Claire in the central portion of the basin. Milstein (1989) mapped the Eau Claire showing a maximum thickness of over 800 feet near the central basin and thinning to less than 100 feet along the eastern margin of the state (Figure 5.2-9a). The Eau Claire is mapped by

Milstein (1989) as being about 425 feet thick at the Kalamazoo site, verified by local well log data which show the Eau Claire to be about 400-430 feet thick in the Kalamazoo area.

The top of the Eau Claire occurs at about -3,600 feet below mean sea level (MSL, Figure 5.2-9b) in central portions of Kalamazoo County and dips to the northeast, reaching a maximum depth of over 13,000 feet in the center of the Michigan Basin. A structural map constructed on top of the Eau Claire is provided in Figure 5.2-9b. While the lower approximately 200 feet of the Eau Claire is included in the Injection Interval, the uppermost 200 or more feet of the Eau Claire is characterized by a thick shale-rich layer that is included in the Arrestment Interval and provides significant barriers to vertical fluid movement from the Mt. Simon and Lower Eau Claire (see Section 5.3.2.2).

Galesville/Dresbach Sandstone and Franconia Formation

The Galesville/Dresbach Sandstone is also thickest in the central portion of the Michigan Basin, reaching its greatest thickness of over 600 feet in Gladwin County. It is approximately 100-200 feet thick in southwest Michigan and is about 100 feet thick in the Kalamazoo area, verified by site specific data which indicate it to be approximately 102-103 feet thick at the Site. The Galesville/Dresbach generally thickens to the northeast, Figure 5.2-10 is an isopach map of the Galesville/Dresbach. The Galesville/Dresbach is described as medium grained silica-cemented sandstone that may have glauconite and dolomite, with siltstone and shaley units present locally.

The Franconia Formation includes “a wide array of glauconitic dolomitic sandstone, shale, and sandy dolomite” that is sometimes indistinguishable from the underlying Galesville/Dresbach Sandstone. Milstein (1989) states that the Franconia is composed of a light pink to gray quartz sandstone that contains pyrite and abundant glauconite, but can be readily identified by gamma ray log. The Franconia has a maximum thickness of about 800 feet, and is estimated to be about 150 feet thick in the Kalamazoo Area (Figure 5.2-11).

Trempealeau Formation

The Trempealeau is a buff to light brown dolomite that can be sandy, shaley, and cherty, with some glauconite. Literature suggests that the formation is likely composed (from the top to the base) of the St. Lawrence, Lodi, and Jordan members (WMU, 1981). The St. Lawrence member is a sandy dolomite with dolomitic shales. The Lodi is a sandy dolomite with interbedded stringers of shale and sandstone, while the Jordan sandstone is fine grained quartz sandstone to sandy dolomite. This formation represents a transition between underlying sand-rich units and overlying carbonate rich intervals. The Trempealeau Formation is about 200-275 feet thick below the Kalamazoo area, and is more than 900 feet thick in the center of the Michigan Basin. Figure 5.2-12a is an isopach of the Trempealeau Formation and Figure 5.2-12b is a regional structure contour map constructed at the top of the Trempealeau.

5.2.3.3 Middle and Upper Ordovician Units

Middle and Upper Ordovician Units include several formation of varying lithologic characteristics that provide added layers of protection for the USDW in the event of fluid movement from the Confining Zone. These include the Prairie de Chien, St. Peter/Glenwood Formation, Black River/Trenton Formation and Utica Shale.

Prairie du Chien Group

The Prairie du Chien Group is Lower Ordovician in age, and consists of various layers primarily comprised of gray, sandy dolomite and dolomitic sandstone that includes the Shakopee [Foster] Formation as well as other major units identified by WMU (1981) as the Oneota Dolomite, New Richmond Sandstone, and Shakopee Dolomite. WMU (1981) states that in the subsurface “the entire Prairie du Chien Group has characteristics similar to dolomite”, and indicates that in some areas (near subcrop) the Prairie du Chien is porous. Smith, et al. (1993) described the Prairie du Chien Group as carbonate-dominated mixed carbonate siliciclastic sediments “deposited in and adjacent to shallow tropical seas that flooded most of the central North American craton during the Early Ordovician…[and] consists of sandy, silty and relatively pure dolomites and minor quartzarenites that underwent intermittent reworking by waves and unidirectional currents”. Smith et al. also state that “In the subsurface of the Michigan basin, dolomites of the Oneota Formation overlie silty-glauconitic dolomites of presumed Trempealeauan age, and are overlain by silty-sandy dolomites and dolomitic siltstone of the basal Shakopee [Foster] Formation”. The Shakopee is heterogeneous and consists of interbedded silty and sandy dolomites, with dolomitic siltstones, sandstones and shales. In the Central Michigan basin, Smith et al. (1993) state that the Shakopee is overlain by shales of varying thickness, that in turn are overlain by the St. Peter Sandstone.

The contact between the Prairie du Chien and overlying units is unconformable in many locations. WMU (1981) indicates that the Prairie du Chien is overlain by the Post Knox Unconformity. Sandstone intervals above the Prairie du Chien (e.g. St. Peter) are discussed by some authors as part of the Prairie du Chien Group. However, since the sandstone sequences are not present in the Kalamazoo area, the Prairie du Chien only includes the carbonate sequences for the purposes of this petition. The Prairie du Chien of Michigan is generally represented by this same name in Illinois, Wisconsin, and Indiana, and it is equivalent to the upper part of the undifferentiated Knox Dolomite of Ohio and to the Beekmantown Dolomite, the Gunter Sandstone, the Gasconade Dolomite, the Roubidoux Formation, the Jefferson City Dolomite, and the Cotter Dolomite of Kentucky.

Milstein (1983) mapped the Prairie du Chien as about 400 feet thick and occurring 2,750 feet below MSL (Figures 5.2-13a and 5.2-13b) at the P&U site and in the general Kalamazoo area. The Prairie du Chien is a gas producer in limited portions of the central Michigan Basin, with the deepest of these producing from wells more than 10,000 feet below ground surface. No production was identified in Kalamazoo County from this formation.

St. Peter Sandstone/Glenwood Formation

The St. Peter Sandstone occurs unconformably above the Prairie du Chien, and is present in northern portions of the Michigan Basin. The St. Peter absent in southern Michigan (Figure 5.2-14).

St. Peter/Glenwood can be a prolific oil producer in isolated areas of Michigan as indicated by Nadon, et al. (2000):

> "The Middle Ordovician St. Peter Sandstone and Glenwood Formation (Ancell Group) represent a significant target for gas exploration at the base of the Tippecanoe sequence in the Michigan basin. Core and well log data show that the St. Peter-Glenwood interval contains numerous carbonate units that provide the basis for both regional correlation and subdivision of the section into at least 20 high-frequency sequences. The temporal resolution afforded by these sequences allows a detailed analysis of sediment partitioning as the basin evolved. The spatial distribution of the basal sequences illustrates the pronounced east-to-west onlap of the Wisconsin arch. An abrupt increase in sequence thickness up section indicates that a major episode of basin-centered subsidence began during middle St. Peter deposition and continued through the deposition of the Glenwood Formation. The upper sequences show a significant beveling of the Glenwood Formation and the top of the St. Peter Sandstone

> in the north, south, and southeast areas of the basin prior to deposition of the overlying Black River carbonates. Although eustatic sea level changes were undoubtedly operating at several scales, the facies distribution of this mixed clastic/carbonate system also documents significant changes of local and regional tectonics."

The Glenwood Shale is dolomitic and sandy shale that occurs in the northwestern portion of the Michigan Basin. It thins to the east and is a greenish-grey shale in central Michigan. It is persistent and mappable throughout the Basin but typically is no greater than 20 feet thick. WMU (1981) suggests that this unit may serve as a Confining Zone, as it is "thought to be a barrier to the movement of hydrocarbons from the Black River Group into the underlying Prairie du Chien and Cambrian units". Figure 5.2-14 is an isopach map of the Glenwood Shale/St. Peter showing that these units are absent in the Kalamazoo area.

Black River/Trenton Groups

The Black River Formation is composed of thick, undifferentiated dense brown/grey micritic limestones with cherty intervals and an altered volcanic ash layer called the Black River Shale. This shale is a thick yet distinctive bed, of limited extent, occurring in southern Michigan. Near outcrop, the Black River Group may produce water from solution joints/fractures, but is "quite impermeable except where it has been dolomitized" in areas away from subcrop (WMU, 1981). The Trenton Group consists of several hundred feet of light brown to brown limestone. It is 200-450 feet thick across the Michigan Basin. WMU (1981) states that "although the Trenton limestones are relatively impermeable, the possible presence of fractures and dolomitized zones could preclude its use as confining layer". The principle porosity zones are in areas of dolomitization. Local data presented in Section 5.2.2.3 indicates the layer locally does have "cap-rock" properties". The Black River/Trenton is about 500 feet thick at the P&U facility in central Kalamazoo County based on well log data. Figure 5.2-15 is a structure contour constructed at the top of the Trenton.

Wilson et al. (2001) describe the Black River and Trenton Formations as follows:

> "The overlying section is another great sheet of Middle Ordovician carbonate, the Black River and Trenton formations. These strata [Black River and Trenton] host the largest single oil field in the state (Albion-Scipio). The lower part of the Middle Ordovician carbonate, the Black River Formation, consists of very micritic dense lime mudstone to wackestone with some brachiopods and possesses nodules of brown chert. Dark shale laminae in the Black River may indicate that source beds for petroleum occur within this carbonate sheet, in fact as high as the top of the Trenton Formation….Gamma-ray

and neutron-porosity-density logs show that the Black River, like the Trenton, is thinner and more argillaceous in the northeast quadrant of the basin…"

Richmond Group/Utica Shale

The Richmond Group unconformably overlies the Trenton and Black River Groups. Regionally, it contains the Collingwood Shale and Utica Shale. The Collingwood can also be a shaley limestone but the formation is not reported to be present in southern portions of the State. The Trenton-Richmond Group (i.e. Utica Shale) stratigraphic boundary is "a widely recognized and traceable stratigraphic boundary throughout the basin, well-marked on both petrophysical and lithologic logs and also visible seismically. It is commonly used as a datum for structure contour maps and is assumed to be a chronostratigraphic surface" (WMU, 1981). Note that various authors disagree whether the Trenton-Utica contact is conformable.

The Utica Shale is upper Ordovician in age and records the influx of argillaceous mud into the depositional system. As a result, the Utica is a hard, dark gray to greenish black calcareous shale that is "homogenous throughout" the Michigan Basin (WMU, 1981). Thickness varies from 150 to 400 feet thick (Figure 5.2-16), and it is about 250 feet thick in the central portion of Kalamazoo County. WMU (1981) states that "the very low permeability of this rather thick shale coupled with the fact that it forms the seal on known hydrocarbon traps indicates that it is an excellent confining layer".

5.2.3.4 Silurian Unit

As with the Ordovician, thick units are present that offer additional confinement. These include the Cataract Group, Niagara, Salina and Bass Islands. The presence of low permeability units like shales and salts serve to impede vertical fluid movement.

Cataract Group

The Cataract Group occurs at the base of the Silurian section, and consists of the upper Cabot Head Shale and lower Manitoulin Dolomite. The Cabot Head is composed of shale. The Manitoulin is buff to light brown dolomite, locally cherty with interbedded shale or shaley dolomite (Ells, 1967). In the Kalamazoo area, the combined thickness of Cataract sequence is about 300 feet based on site geologic data.

Niagara

Matzkanin, et al. (1977) summarize the geology of the Niagaran as follows:

> "Niagara rocks in the subsurface are predominantly dolomites and limestones with scattered regional occurrences of cherty zones and thin shale beds. These rocks range in thickness from less than 100 feet in the basin interior to more than 1,000 feet at the basin margin…. pinnacle reef complexes [occur] a few miles basinward from the thick carbonate bank. Reefs, reef associated sediments, and biostromes occur at various stratigraphic levels within the Salina-Niagara Group. Reefs range in size from small isolated masses 10 feet in diameter to large complexes several hundred acres in extent and vary in height from a few feet to more than 500 feet. Most reefs in the subsurface appear to be coral-algal-stromatoporoid mounds with occurrences of brecciation and a variety of fossil debris from shelly organisms. "Pay zone" porosity appears to be developed by preferential solution of coral skeletons and invertebrate remains from the fossiliferous rock by groundwaters. Dolomitization of limestone reefs frequently plays an important role in the development of porosity. Occasionally evaporite infilling destroys potentially productive porosity."

WMU (1981) states that "in the subsurface of the Southern Peninsula of Michigan, rock of the Middle Silurian Niagara Group form gradation zones with distinctive rock characteristics. In the central part of the basin the Niagara Group consists of a thin (50-120 feet) dense limestone (micrite) termed the "basinal facies" that grades outward into a dolomitic limestone….then grades into a porous dolomite…termed the "shelf facies". The shelf facies… [that is] about 120 to 300 feet [thick]. The shelf facies is characterized by the presence of locally thick areas in the form of "pinnacle" reefs. Outwash this facies grades outward around the shelf facies into a thick (300 feet to 500 feet) zone…called the "bank facies". This zone is composed of porous and permeable dolomite and extends southward into Indiana and Ohio and northward into the outcrop area".

Data presented in WMU (1981) suggest that the Kalamazoo area occurs within the shelf and barrier reef facies. Log and map data suggest that the Niagaran is about 200 - 350 feet thick in Kalamazoo County. The Niagara is a prolific oil and gas producer in Michigan, and data suggest that this was a primary oil and gas drilling target in portions of southern Michigan. Figure 5.2-17a is a map presenting the depositional systems within the Niagaran and isopach trends, while Figure 5.2-17b is a structure contour map constructed at the top of the Niagaran.

Salina Group

Matzkanin et al. (1977) summarizes the Salina Group as follows:

> "The Salina Group contains evaporite, carbonate, and shale stratigraphic units. The A-1 Evaporite, A-1 Carbonate, A-2 Evaporite, and A-2 Carbonate units are of particular interest where Niagaran reefs are present. While the A-1 Evaporite is a clean salt over most of the Michigan basin interior, the unit grades laterally into an anhydrite that thins and pinches out against the flanks of reef complexes. The A-1 Carbonate is essentially a dark colored limestone, dolomite, or both in non-reef locations. In the vicinity of reefs, the A-1 Carbonate may be completely or partially dolomitized and exhibits depositional thinning over the reef and margin reef complexes. The A-2 Evaporite is nearly a pure salt in the deeper parts of the basin, while near reefs the unit is generally represented entirely by anhydrite. Partial dolomitization and some depositional thinning occur in the A-2 Carbonate where it overlays reef complexes".

WMU (1981) states that the Salina Group is a "thick sequence of carbonate, anhydrite, silt and shale" that is restricted in areal extent to the approximate location of the Niagara Formation. The unit grades upward from the Basal "A" member (A-1 Evaporite, A-1 Carbonate, A-2 Evaporite and A-2 Carbonate) through F member, and is composed of interbedded shales, limestones and salts. The Salina-Bass Island group ranges in thickness from less than 100 feet to over 700 feet throughout the Michigan Basin. It should be noted that the Salina may contain several hundred feet of bedded salt, in total. Log data suggest that the Salina is approximately 400 feet thick in central Kalamazoo County. Figure 5.2-18a is an isopach of the A-2 evaporite member of the Salina which is present only in northern portions of Kalamazoo County. Figure 5.2-18b is a structure contour map constructed on the top of the Salina.

Bass Islands

The Bass Island Group conformably overlies the Salina. The Bass Island Group in the Michigan Basin generally consists of dense, buff dolomite and the upper part is sparsely oolitic. Lower in the section, gray argillaceous dolomites, shaley dolomites, and brown beds are present (Ells, 1967). WMU, (1981) states that the Bass Islands is described as a thick sequence of fine-grained dolomites that has floating anhydrite and celestite crystals, as well as some salt in central portions of the Michigan Basin Group. Regional data suggest the Bass Islands Group ranges from 0-750 feet thick in the Basin center, and can be more than 100 feet thick in central Kalamazoo County.

5.2.3.5 Devonian – Mississippian Units

Devonian-aged units present in the area include the Bois Blanc/Detroit River Group, Dundee Formation, Bell Shale, Traverse Group, Antrim, and Ellsworth Formations. Mississippian units include the Coldwater Shale and Marshal Shale. Devonian units are, in total, approximately 990 feet thick in central Kalamazoo County. The Devonian-Mississippian units are discussed individually, below.

Detroit River Group

WMU (1981) states that the Detroit River Group (Figure 5.2-4) includes the Garden Island, Bois Blanc, Sylvania, Amherstburg, and Lucas Formations. The Detroit River Group is about 259 feet thick in central Kalamazoo County based on log data. The Bois Blanc is composed of dolomite and cherty dolomites, with upper limestone-rich intervals. The Sylvania is sandstone, composed of well-rounded and sorted fine to medium grained quartzitic sandstone with thick chert and dolomitic intervals that is present in northwestern areas of the Basin. The Amherstburg is a dark brown to black carbonaceous limestone that is present in most of the Michigan Basin. It is poorly bedded and dense, and present only in extreme northern portions of Kalamazoo County (WMU, 1981).

While the Detroit River includes the above formations, WMU (1981) indicates that it is “general practice” to only call that portion of the column between the top of the Amherstburg and Dundee the “Detroit River” and WMU (1981) states this portion of the column is sometimes referred to as the “Lucas Formation”. This portion of the column includes the Richfield Member, which is a sequence of interbedded limestone, dolomite and anhydrite with minor amounts of sand, a massive anhydrite unit, and the Horner Evaporite composed of interbedded anhydrite, limestone, and salt. In total, the Detroit River is mapped as being approximately 250-260 feet thick in central Kalamazoo County based on log data. Figure 5.2-19a is an isopach map of the Detroit River Group (Lucas member) while Figure 5.2-19b is a structure contour map constructed at the top of the Detroit River Group.

Dundee Limestone

The Devonian age Dundee is predominately a carbonate section ranging from dense, fine-grained, light colored limestones on the east side of the state to coarse-textured bioclastic limestone (with portions secondarily dolomitized) in the central part of the state. In the central portion of Kalamazoo County, the Dundee is about 50-60 feet thick. The Dundee is a prolific oil and gas producing formation in portions of the Michigan Basin. Recent examination of oil production in the Dundee and structural trends reveal a correlation attributed by some authors to hydrothermal dolomitization (e.g. Davies and Smith, 2006). The occurrence is attributed to movement of hydrothermal fluids along basement-rooted faults with subsequent dolomitization of carbonate sequences, primarily the Dundee. As shown in Figure 5.2-3, none of these structural trends occurs in Kalamazoo County. No commercial accumulations of Dundee hydrocarbons in Kalamazoo County have been identified. Figure 5.2-20a is an isopach map of the Dundee, and Figure 5.2-20b is a structure contour map of the Dundee top.

Bell Shale

The Devonian age Bell Shale is typically soft, gray, gummy and silty shale containing scattered fossil fragments. The Bell Shale is not present in the Kalamazoo area. Figure 5.2-21a is a regional isopach map of the Bell Shale and Figure 5.2-21b is a structure contour map constructed at the top of the Bell Shale.

Traverse Group

The Traverse Group occurs above the Bell Shale (or the Dundee), and includes what is locally described as the Traverse Limestone and Traverse Formation. Both are described below. The Traverse Group is approximately 200-300 feet thick in Kalamazoo County.

<u>Traverse Limestone.</u> In western Michigan, the Devonian-age Traverse Limestone is dominantly a gray to gray-brown limestone, with lesser gray shales. A few anhydrite stringers may also be present. To the east, the Traverse Limestone becomes increasingly shaley, and in southeastern Michigan the unit is composed almost entirely of shale.

<u>Traverse Formation.</u> Below the Traverse Limestone is the Traverse Formation, and in the P&U area this interval is composed of interbedded limestone and shale zone that is described as gray-tan and calcareous. This unit is described locally as interbedded tan-buff limestones that may be hard dense and fossiliferous. The Traverse is an oil-producing formation in southern Michigan in, for example, Kent, Ottawa, and Allegan counties.

Antrim Shale

The Antrim Shale conformably overlies the Traverse Group and has been subdivided by some authors into a lower “dark” Antrim and upper “light” Antrim, both of which consist of dark or light gray shales, respectively. Geophysical log signatures indicate that it has low permeability. Figure 5.2-22a is an isopach of the Antrim Formation and Figure 5.2-22b is a structure contour map constructed at the top of the Antrim Shale. The unit is approximately 100 feet thick in the central portions of Kalamazoo County.

Ellsworth Shale

The Ellsworth Shale conformably overlies the Antrim Shale and is composed of gray-green shale with minor amounts of sandstone and limestone. Geophysical log signatures indicate that it has very low permeability. The Ellsworth is approximately 335 feet thick in central Kalamazoo County.

Coldwater Shale

The Coldwater Formation conformably overlies the Ellsworth Formation. It consists of grey shale. The Coldwater subcrops throughout the majority of Kalamazoo County. At its thickest point, north of Saginaw Bay, the Coldwater is as thick as 1,300 feet (WMU, 1981). The unit is mapped as being 600 feet thick in Kalamazoo County, although local data suggest it may thin somewhat to the south. Figure 5.2-23a is a map presented in WMU (1981) that did not extend to the P&U site area because the Coldwater Shale subcrops in South Western Michigan. Figure 5.2-23b is a regional structure contour map of the Coldwater Shale.

Marshall Shales and Sandstones

The Marshal Shales/Sandstones occurs above the Coldwater shale, but presence and thickness in southwestern Michigan is highly variable due to erosion in some areas. For more information regarding the local occurrence of this formation, see Section 5.3.3.2 and Chapter 4, Hydrology of USDWs. The unit is present only in extreme northeastern portions of Kalamazoo County.

5.2.3.6 Glacial Drift

Figure 5.2-24 is a generalized isopach of the Glacial Drift showing that the Drift is as much as 350-400 feet thick in the Kalamazoo County. Sands are quartzitic and are medium to coarse grained in size, and clays are grey to light grey. Chapter 4 presents additional information regarding the Glacial Drift in the area.

5.2.4 Regional Hydrology

WMU (1981) provided an evaluation of regional groundwater systems in Michigan, and assigned Kalamazoo County to the Southwest Region 2 area (Figure 5.2-25). According to this source, the primary source of potable groundwater is the Glacial Drift. The Glacial Drift has been determined to be the lowermost USDW at the P&U site. Chapter 4 presents more detailed discussion of the USDW and water resources in the area that is summarized below.

5.2.4.1 Regional Surface Water Data

Many surface water features occur in the vicinity of the P&U facility. Specifically, Upjohn Pond abuts the east side of the facility, while Long Lake, Austin Lake, and West Lake occur south of the Site. Portage Creek occurs west of the site and drains to the Kalamazoo River which is about 5 miles north of the P&U Site. Kalamazoo County is divided literally in half by two major watersheds: the Kalamazoo River Watershed on the northern portion of the County and St. Joseph Watershed in southern portions of the county. The P&U facility occurs on the southern margin of the Kalamazoo River Watershed. Rheaume (1991) subdivided the state into different provinces based on drainage systems and assigned Kalamazoo County as part of Hydrologic Province 7.

The Michigan Department of Environmental Quality states that of the 13 municipalities providing community water supplies in the county, all acquire drinking water from groundwater sources including the cities of Kalamazoo and Portage (http://www.michigan.gov/ documents/ deq/ CWS_List_by_County_426701_7.pdfWMU). Data available from the same website indicates that groundwater has always been the primary source of municipal drinking water. WMU (1981) states that water supply wells for the cities of Kalamazoo and Portage are in the "drift" aquifer, inferring none of the public supply wells for these cities originates from bedrock. While the same source indicates six wells in the county may be completed in bedrock, examination of publicly available data do not show any well in the city of Kalamazoo and Portage area produces from bedrock aquifers. Additional discussion of shallow hydrogeology is included in

Section 4. As of 2014, the cities of Kalamazoo and Portage continue to obtain its city water supply from drift groundwater wells.

5.2.4.2 Regional Unconsolidated Aquifer

Kalamazoo County occurs at the confluence/intersection of the Lake Michigan glacial lobe and Saginaw glacial lobe. Landforms in the county are typically either outwash or morainal in origin. The area hosts various moraines and associated outwash plains, with the Outer Kalamazoo Moraine occurring northwest of the Site and the Galesburg-Vickesburg outwash plain below the P&U facility. WMU (1981) stats that over eighteen different moraine systems occur in southwestern Michigan. Local data suggest that glacial deposits are approximately 300 - 400 feet thick in the Kalamazoo area (Figure 5.2-24). Additionally, references such as Rheaume 1991, and WMU 1981 verify that the glacial aquifers in Kalamazoo County may be greater than 300 feet thick.

WMU (1981) indicates that water well depth in the Kalamazoo County may exceed 200 feet. WMU (1981) evaluated data from 369 groundwater wells in the county and found all were completed in glacial drift. Well capacity for the evaluated wells ranged from 61 to 2,100 gpm. Specific capacity in the glacial drift aquifer varied from 4 – 182 gpm/ft. in the Kalamazoo County wells, while transmissivity varied from 35,000 gpd/ft. to 230,000 gpd/ft. The coefficient of storage varied from 0.19 to 6×10^{-5} (WMU, 1981).

WMU (1981) indicates that the Glacial Drift in southwestern Michigan exhibits TDS concentration between 192-530 ppm in wells measured for that study. The quantity and quality of water available in the drift is dependent on the type of glacial deposit present at a specific site.

5.2.4.3 Regional Bedrock Aquifer

Bedrock groundwater wells are extremely uncommon in Kalamazoo County. Rheaume (1991) states:

> “Ground-water resources in Province 7 [including Kalamazoo County] are abundant; however, production is almost entirely from glacial deposits, which range from 100 to 600 feet in thickness (Passero and others, 1981, pi. 15). Yields greater than 500 gal/min

are common for wells screened in coarse-textured sand and gravel outwash plains in the southwestern and southeastern parts of the province. The Kalamazoo-Portage metropolitan area is the second largest user of ground water in the State (8 billion gal/yr), all withdrawn from glacial deposits (Huffman and Whited, 1988, p. 23)…. Mississippian bedrock, consisting mostly of the Coldwater Shale, underlies glacial deposits throughout the province, and it is extremely low yielding (less than 5 gal/min) (Twenter, 1966a, pi. b)."

WMU (1981) suggests that there are at least six Mississippian bedrock aquifers in Kalamazoo County, but literally no data are available regarding water quality or yield for these wells and recent well searches showed no indication of any current well producing from the bedrock (see Section 4 for additional information). Supporting this, Deutsch, et al (1960) states that while consolidated sediments lie beneath glacial drift in the Kalamazoo area, "None of these rock formations are known to supply fresh water to wells in the Kalamazoo area".

5.2.4.4 Regional Hydrology of the Mt. Simon and Munising Group

Based on review of available state of Michigan databases, only a limited number of wells have penetrated into the Munising Group. This can make precise evaluation of original pressures, fluid quality trends, and natural hydraulic gradients a challenge for the Michigan Basin. A number of authors including Vugrinovich (1986), and Gupta (1997) have presented analyses of available data and attempted to establish a framework for the hydrogeology of the Mt. Simon as it is encountered in the deeper portions of basins within Michigan, Illinois, Indiana and Ohio. Other authors have provided analyses of a more general nature regarding deep-basin flow and conditions in the Mt. Simon as discussed further in Chapter 8 of this document.

Original formation pressure at a specific reference depth is used in the characterization of the site and in the evaluation of containment. Although no literature information is available regarding Mt. Simon pressures for southwestern Michigan, local and regional data are available regarding reservoir pressures encountered in the Mt. Simon during installation of Class I wells in the region and P&U Well Nos. 3 and 4. Table 7-4a and 7-4b of this document present historic static pressures in the P&U Well Nos. 3 and 4 and other wells in the region.

Natural aquifer flows are well documented for shallow aquifers, but detailed and reliable data for deep, confined aquifers is scarce. Various studies have shown very slow to nearly static conditions in the deep subsurface. Flow rates in deep saline aquifers from studies presented in Clark (1988) were on the order of inches per year. The few studies in the Mt. Simon Formation [Nealon (1982); Clifford (1973), Bond (1972)] and the Frio Formation on the Texas Gulf Coast [Kreitler and Akhter (1987)] demonstrate the complexities of the problem and the limitations of some conventional hydrological methods. Clifford (1973) applied a gravity segregation technique to construct a potentiometric map of head in the Mt. Simon in Michigan. He was then able to estimate the general magnitude and direction of natural potential gradient in the Mt. Simon and, with ranges of values for permeability and porosity in the Mt. Simon from a variety of sources, make order of magnitude estimates for natural flow in the Mt. Simon. Clifford's data indicate that natural Mt. Simon flow on a regional scale in southwestern Michigan is southwesterly and likely has a velocity of less than six inches per year. A hydrogeologic assessment of the "basal sandstone" (Mt. Simon and Eau Claire Formations) of Illinois, Indiana, Michigan, and Ohio was prepared by the UIPC in 1989. Pressure data were used with measured fluid densities to compute pressure heads. Based on mapping these total head values as equivalent fresh water heads referenced to sea level, it was concluded that natural velocity in the Mt. Simon varies from nearly stagnant in the deep basins to an average of approximately 0.5 feet per year in northeastern Indiana. Based on the Kalamazoo location it is probable that velocity coming from the deep basin is only on the order of 1 or 2 inches per year.

Gupta and Bair (1997) and Gupta and Sminchak (2006) also evaluated regional brine movement in the Mt. Simon by conducting simulation studies for a multi-state area accounting for variable brine density in the Mt. Simon and overlying units. According to Gupta and Sminchak (2006), "Fluid flow in deep saline formations in the Midwest U.S. is controlled by topography, geologic structure, permeability variations, and variable density. Flow in deeper basins appears to be influenced primarily by structures, while flow in the shallow layers is more controlled by gravitational forces and topography. Based on the variable density heads and boundary conditions the flow in the deeper layers is generally part of the regional and extremely slow flow paths, that are ideal for large-scale storage". In addition to downward flow into the Mt. Simon in the vicinity of Kalamazoo, a southwesterly flow direction of slow brine movement is indicated in the Mt. Simon. A gradient of 1×10^{-5} to 4×10^{-5} ft./ft. appears to be indicative of basal aquifer conditions in southwestern Michigan based on these studies. Depending on the effective permeability and porosity through which the fluid is traveling, these gradients are consistent with an interstitial fluid velocity of approximately an inch per year. Since over a large scale, heterogeneity will yield some restrictions along the flow path, a velocity of less than one inch per year is possible. Barnes et al. (2009) chose to represent large scale Mt. Simon permeability as 33 md. As discussed further in Chapter 8, sensitivity modeling of the low density plume has included the assumption that this natural hydraulic gradient is moving fluid to the southwest up out of the Michigan Basin oriented with the up-dip direction of buoyant plume migration to maximize drift.

5.2.5 Regional Seismicity

The Kalamazoo area of the Michigan Basin is designated as a minor seismic risk area by the USGS (http://earthquake.usgs.gov/regional/states/michigan/hazards.php). The area has a peak ground acceleration of 4-6 percent *g* (standard gravity) (Figure 5.2-26). Earthquaketrack.com states that southwest Michigan has experienced no measurable earthquakes during the past year (2013). USGS data indicates the most recent earthquake in the southwest midway region occurred in 2012; it had a magnitude 3.0 and epicenter depth of 4km, and occurred (originated near) Sturgis, Michigan. An earthquake occurred near Kokomo, Indiana in 2010 (3.8 magnitude), but this is over 150 miles south of Kalamazoo. Also, 19 years ago a 3.5 magnitude earthquake occurred near Waverly Michigan (Lansing), with a 5km epicenter depth. The most recent earthquake with a magnitude greater than 4.5 occurred more than 60 years ago on August 9, 1947. It damaged chimneys and cracked plaster over a large area of south-central Michigan and affected a total area of about 50,000 square miles, including points north to Muskegon and Saginaw and parts of Illinois, Indiana, and Wisconsin. The cities of Athens, Bronson, Coldwater, Colon, Matteson Lake, Sherwood, and Union City in the south-central part of the State all experienced intensity VI effects. This earthquake was centered over 35 miles southeast of Kalamazoo (USGS, 2014). Section 5.3.5 presents additional discussion of local seismic activity and the potential for induced seismicity in the Kalamazoo area.

5.3 LOCAL GEOLOGIC ANALYSIS

As shown in Figure 5.3-1 and as detailed in Figures 5.3-2 and 5.3-3, two wells penetrate into the Mt. Simon within a two-mile radius around the P&U site, those being the P&U Well Nos. 3 and 4. Table 5-1 below presents the formal well locations, names and abbreviated names that are used in this text for these two wells. Data from these wells were used to assess the local geology and to define the characteristics of the Injection Zone and Confining Zones. Additionally, due to the limited local core and other data pertaining to bedrock units, select data from Ottawa County Warner-Lambert Well Nos. 3, 4 and 5 are included, as needed (see Section 5.3.1 for additional information). When taken in conjunction with regional data, local well data show that the Injection Zone (comprised of the Injection Interval and Arrestment Interval) and Confining Zones are thick, laterally continuous, and well defined. A brief summary of the local stratigraphic column is presented below, followed by detailed information pertaining to the physical characteristics of each unit. Data from this section was obtained from numerous sources, including the previous 1989 Land Ban Petition and more recent permit application submissions.

Table 5-1. P&U Injection Well Location and Well Names

Well Location	Formal Well Name on Well Log	API Number	Well Name this Report
T3S R11W Sec 14 SW SE NE	The Upjohn Company Upjohn #3	21-077-00327-70-00	Well No. 3 or P&U Well No. 3
T3S R11W Sec 14 NE SE	The Upjohn Company Upjohn #4	21-077-00137-70-00	Well No. 4 or P&U Well No. 4

Figure 5.3-2 presents a regional SW-NE cross section that transects the site for the Mt. Simon portion of the geologic column through southeastern Michigan (modified from Barnes et al. 2009). Figure 5.3-3 is a local NW-SE cross section showing the stratigraphic sequence at the Site. Note that the lack of deepwell data in the P&U area precludes the generation of detailed local cross sections. Site well geophysical logs are included in Appendix 5-I.

Local isopach and structure contour maps were generated for numerous formations of interest in the Kalamazoo area. Maps were constructed based on a combination of well log picks and formation tops from the Michigan Department of Environmental Quality well database. Appendix 5-II includes a data table that presents the formation top and isopach (thickness) values used to generate maps referenced in Section 5.3. Formation depths are usually referenced as an “average depth” at the P&U site or to Well No. 4 unless otherwise specified. Section 5.3 unit or formation thickness and formation top information was derived from wellsite geologist formation descriptions at the P&U site, but every value may not always directly correspond to the values presented on the associated structure contour and isopach maps. These small discrepancies are due to different methodologies for "picking" formations (i.e. during drilling vs. well log analysis by the Michigan DEQ). Any significant differences between the data sources are identified and discussed in the text as appropriate, but minor variations of a few feet do not impact conclusions and are not explained further in subsequent sections of this document.

5.3.1 Local Structural Geology

Regional structure contour maps are presented as Figures 5.2-7, and 5.2.8b through 5.2.24b. Local structure contour maps were constructed based on these maps, with refinement using well data available from the P&U (Site) area, including well logs and the Michigan DEQ Formation Tops database. Consistent with regional characterization discussed in Section 5.2, maps indicate that there are no major or mappable structural features within the Site area, and site-specific data also suggest that there are no faults that transect the Injection Zone or Confining Zone. That is, the Injection Interval, Arrestment Interval, Confining Zone, and overlying units are laterally continuous, with no abrupt changes in thickness or lithology within a 20-mile radius of the Site. Detailed information about individual formations and local stratigraphic characteristics of critical units are presented in Section 5.3.2.

A site-specific structure contour map was constructed at the top of the Mt. Simon using the gamma ray signature identified by Barnes et al. (2009) as the top of the Mt. Simon. Figure 5.3-4a presents this surface. As shown in this figure, the Mt. Simon dips approximately 40 feet per mile (less than 0.55 degrees) to the northeast over a larger area centered on the P&U site, and dip remains relatively consistent throughout Kalamazoo County. Local dip direction is approximately N 37° E and the direction appears to be consistent in local and regional analyses.

The structural configuration of the Mt. Simon is an important aspect of fluid migration calculations presented in Section 8 of this Petition Renewal Application, but there is some uncertainty associated with the values presented on the constructed map due to the extremely limited well control. To evaluate uncertainties associated with the calculated dip, work from several authors including Barnes et al. (2009), Milstein (1988, 1989), and others were used to verify the structure contour values, local dip, and well control data. As shown in Figure 5.3-4b, a potential uncertainty of less than +/- 20° for the direction of the dip projected across the 5-mile

AOR was determined based on comparison of local data with regional interpretations. These uncertainties have been considered in the projections presented in Section 8.

Barnes et al. (2009) prepared a detailed report addressing the Mt. Simon and injection potential in southern Michigan, and this document among others, served as an important resource to verify local maps and calculations. For example, overburden thickness is key to available porosity (as discussed in Section 5.3.2.2 below), so a regional overburden map was constructed. To verify these values, the same map constructed by Barnes et al. is compared to the regional well picks, with generally good agreement (Figure 5.3-4c). Figure 5.3-4d is a local Mt. Simon isopach map.

While significant research into the injection capabilities of the Mt. Simon has increased the regional and local understanding of this formation, the fundamental characteristics of the Mt. Simon as presented in the 1989 petition remain unchanged. Maps and interpretations have been updated, and new porosity, permeability, rock characteristics and other data have been added to ensure consistency with recent literature and research.

5.3.2 Local Stratigraphy

Stratigraphic data from Well Nos. 3 and 4 log, cuttings, and core information were used to characterize local geology. Table 5-2 presents the depth to formation tops based on the two P&U wells. Table 5-3 presents the interval thickness, which is typically the thickness of the associated formation or unit.

Table 5-2. Formation or Unit Tops at the P&U Site

Formation	Well No.3 Depth to Top From KB (ft)	Well No.4 Depth to Top From KB (ft)
Ground Level (feet ASL)	871	863
Kelly Bushing (feet ASL)	885	874
Glacial Drift	0 (ground surface)	0 (ground surface)
Coldwater Shale	330	370
Ellsworth Shale	770	765
Antrim Shale	1143	1,134
Traverse Group	1,234	1,203
Dundee Limestone	1,452	1,450

Formation	Well No.3 Depth to Top From KB (ft)	Well No.4 Depth to Top From KB (ft)
Detroit River Group	1,503	1,508
Bass Island Group	1,762	1,750
Salina Group	1,807	1,795
Niagara Group	2,228	2,201
Cabot Head Shale	2,551	2,546
Manitoulin Dolomite	2,582	2,579
Utica Shale	2,865	2,860
Trenton	3,110	3,102
Black River Group	3,436	3,431
Prairie du Chien Group	3,608	3,596
Trempealeau Formation	4,002	3,992
Franconia Formation	4,254	4,254
Galesville/Dresbach	4,429	4,417
Eau Claire Formation	4,530	4,520
Mt. Simon Sandstone	4,964	4,950
Pre-Cambrian (estimated depth)*	5,617	5,600 (est)

* Depth in Well No. 3 based on mud log, not verified by geophysical log. Well No.4 encountered granite-rich sediments but actual contact with consolidated basement is likely deeper.

Table 5-3. Interval Thickness at the P&U site

Formation	Well No.3 Depth to Top From KB (ft)	Well No.4 Depth to Top From KB (ft)
Glacial Drift	330	370
Coldwater Shale	440	395
Ellsworth Shale	373	369
Antrim Shale	91	69
Traverse Group	218	247
Dundee Limestone	56	58
Detroit River Group	254	242
Bass Island Group	45	45
Salina Group	421	406
Niagara Group	323	345
Cabot Head Shale	31	33
Manitoulin Dolomite	283	281
Utica Shale	245	242
Trenton	326	329
Black River Group	172	165
Prairie du Chien Group	394	396

Formation	Well No.3 Depth to Top From KB (ft)	Well No.4 Depth to Top From KB (ft)
Trempealeau Formation	252	262
Franconia Formation	175	163
Galesville/Dresbach	101	103
Eau Claire Formation	434	430
Mt. Simon Sandstone	app.653	app.650

The top of the Mt. Simon was encountered at 4,964 feet RKB in Well No. 3 and 4,950 feet RKB in Well No. 4, and while the TD is likely at or near the consolidated Precambrian basement, exact depth of consolidated bedrock is approximate. The Mt. Simon is approximately 600-650 feet thick below the P&U site.

The permitted Injection Zone for the Site wells consists of the formations between the top of the Franconia/base of the Trempealeau and the Precambrian basement. This interval includes sandstone, shale and carbonates of the Mt. Simon Sandstone, Eau Claire, Galesville/Dresbach, and Franconia (Injection Zone). The permitted injection interval is the Lower Eau Claire to the base of the Munising/Mt. Simon (i.e. top of consolidated Precambrian), the top of the interval is specified by permit as 4,750 feet RKB to TD in both of the two wells. Both wells currently inject into the upper Mt. Simon/Lower Eau Claire Formations.

The Arrestment Interval consists of the Upper Eau Claire, Galesville/Dresbach, and Franconia. The Eau Claire portion of the Arrestment Interval is the first formation overlying the Mt. Simon/Lower Eau Claire and consists of low permeability, shaley, sandstone layers (approximately 10^{-4} md) with interbedded relatively higher permeability sandstones with thin interbedded shale layers. The top of the Eau Claire is approximately 4,520-4,530 feet RKB and the entire Eau Claire is about 430-434 feet thick. The Eau Claire thins to the southwest and thickens to the northeast towards the center of the Michigan basin. The overlying Galesville/Dresbach is comprised of higher permeability sandstone (115 to 2,030 md based on cores obtained from wells in Ottawa and Kalamazoo County) and acts as a buffer unit above the Eau Claire. It is important to note that any pressure ever induced at the top of the Eau Claire would “bleed-off” if it reached the relatively more permeable Galesville/Dresbach layer. Preferential horizontal permeability in this layer would also arrest the potential for any continued vertical pressure driven flow. The Franconia is comprised of about 163-175 feet of interbedded dolomite, siltstone, sandstone, and shale and provides additional cap rock above the Galesville.

The Confining Zone is composed of the Trempealeau Formation with a top found at approximately 4,000 feet RKB at the site (Table 5-2). The Confining Zone is a low porosity dolomite (less than 5%). The Trempealeau is 252-262 feet thick in the P&U area.

5.3.2.1 Precambrian

At TD of 5,617 feet, Well No.3 encountered “granite quartz feldspar and mica, biotite and muscovite” above which occurred “granite wash and sandstone”. Regional structure contour maps constructed on the Precambrian surface indicate that the Precambrian is expected to occur at approximately -4,745 feet below sea level, which is approximately 5,616-5,621 feet RKB at the P&U site wells. Based on this information, top of the Precambrian at the site is estimated to be approximately 5,617-5,620 feet RKB. This is consistent with regional maps generated for the southwestern part of the Michigan Basin. No data are available to suggest the presence of a basal granite wash formation in the area (including the Jacobsville) due to the limited number of Precambrian penetrations in the area, although cutting descriptions imply the presence of unconsolidated granite material at the base of the Mt. Simon in Well No. 3.

5.3.2.2 Cambrian (Injection Zone)

Mt. Simon (Injection Interval)

The Mt. Simon is a thick and ubiquitous sandstone sequence present above the Precambrian in the Kalamazoo area. Figure 5.3-4a is a structure contour map constructed at the top of the Mt. Simon, and Figure 5.3-4d is a local isopach map of the Mt. Simon. These data show that the Mt. Simon is present throughout the area, and is more than 600 feet thick. As shown in Figure 1-1, the Mt. Simon is subdivided into three units at P&U Well No. 4: Upper (4,950-5,060 feet) Middle (5,060-5,467 feet) and Lower (5,467-TD feet). Although these zones cannot be verified by well log at P&U Well No. 3, the zones are likely present based on regional analysis by Barnes (2009).

A core was taken from the Mt. Simon in the P&U No. 4 from 4,951-5009 feet, within the Upper Mt. Simon. Mt. Simon cuttings data and descriptions are also available for Well No. 3. Descriptions of the cores and cuttings indicate that the cored Mt. Simon intervals are composed of sandstone that is gray, medium to large grained sand that is well rounded and porous, coarsening in grain size down section. The sandstone exhibits white to pink coloration increasing down section, with increasing siltstone near the base of the unit that are described as "cavings". Summary data from numerous wells, including more distant Warner-Lambert wells, near Holland approximately 40 - 45 miles to the northwest are presented in Table 5-4a. The location of the Warner-Lambert wells is presented in Figure 5.3-5a.

DOE (2011 and 2012) obtained the P&U Well No. 4 core and reexamined it, among others as part of the CO2 sequestration Arches Simulation Conceptual Model studies to evaluate CO_2 sequestration potential within the Mt. Simon and Eau Claire in Michigan, Indiana, Illinois, Ohio and Kentucky. The study included evaluation of core from five wells in Western Michigan and North Eastern Indiana, including the P&U Well No. 4 core. Summary data from the DOE (2011) study are presented in Table 5-4b, and core locations are presented in Figure 5.3-5b. Additionally, Mt. Simon core descriptions from P&U Well No. 4 are detailed in Table 5-5 as well as core from additional wells in Ottawa County, one of which was included in the DOE study.

Table 5-4a. Lithology of the Mt. Simon Based on Historic Core and Geologic Log Descriptions, P&U Site and Wells in Ottawa County, Michigan

Well Name	Well Location and Date Drilled	Cored Interval	Driller's Sample Interval	Lithologic Description	Mt. Simon Thickness (ft)
P&U Well No 3	T3S R11W Sec 14 SW SE NE July, 1975	Mt. Simon uncored (Galesville/Dresbach cored, see Table 5-9)	4,960-5,617	Sandstone, gray medium to large grained, clear and well rounded, porous, good drilling break. Samples "hard to obtain", using lost circulation material. Sandstone becomes coarser grained downsection, with more pink discoloration. Gray shale and siltstone cavings throughout.	Approximately 653 ft
P&U Well No.4	T3S R11W Sec 14 NE SE September, 1980	Mt. Simon: 4951-5009	No data on record	Core described as sandstone, slightly silty/shaley. Average Porosity: 12% Average Permeabilities Arithmetic: 27 md Harmonic: 9.2 md Geometric: 17 md	Approximately 650 ft.
Warner - Lambert Well No. 3	T5N R15W Sec 20 March and April, 1975	No cores on record	5,082-5,945	Sandstone, fine to medium grained (some coarse grained), well sorted, white to grey (some brown/pink), minor glauconite and shale, dolomite cement and chert down section.	5,080 -TD (5,946) > 866 ft
Warner-Lambert Well No. 4	T5N R15W Sec 20 SWSWSW	No cores on record	5,080-5,946	Sandstone, white with minor pink staining, medium grained, porous, well sorted, friable, silica cement grading to dolomite cement near base with increase in pink staining near base.	5,080 -TD (5,946) > 866 ft
Warner-Lambert Well No. 5	T5N R15 W Sec 29 NWNWNW	Mt. Simon	5,200-5231 (cored interval)	Sandstone, grey, very fine grained with occasional shaley laminae, moderate indurated (average core porosity of 14%, average permeability 145.575 md-Brine)*	5,082- TD (6027) > 945 ft

Table 5-4b. Core Data, Regional Mt. Simon and Eau Claire Wells (DOE, 2011)

Well	API	Location	Formation	Permeability to Air (md)	Porosity (fraction)	Grain Density (g/cc)	Median Pore Throat Radius
Lloyd Cupp 1-11	21-149-31355-01-00	St. Joseph County, MI	Mt. Simon	0.138	0.117	2.660	0.0865
P&U Well No.4		Kalamazoo County, MI	Mt. Simon[1]	0.005	0.022	2.691	0.306
			Mt. Simon	182.695	0.108	2.640	12.4511
BASF 1		Ottawa County, MI	Mt. Simon[1]	78.878	0.106	2.640	6.9670
			Mt. Simon	145.15	0.114	2.628	10.5600
Montague #1	21-121-00280-00-00	Muskegon County, MI	Mt. Simon[1]	0.001	0.012	2.805	0.0702
			Mt. Simon	0.254	0.087	2.631	0.3007
Midwest #2		Lagrange County, IN	Eau Claire[1]	55.355	0.125	2.648	1.4311
			Eau Claire	146.711	0.116	2.626	10.3852

[1] Two portions of the core were tested, resulting in two permeability, porosity, grain density, and median pore throat radius values for these cores.

The P&U Well No 4 core was analyzed for porosity, permeability, storage capacity, and flow capacity as presented in Tables 5-5a-d, below.

Table 5-5a. Porosity Ranges, P&U Well No. 4, Mt. Simon Core

POROSITY RANGE	FEET IN RANGE	AVERAGE POROSITY (%)	AVERAGE PERM (GEOM.)	(ARITH)	FREQUENCY (%)	CUMULATIVE FREQUENCY (%)
2.0 - 4.0	1.0	3.7	7.8	7.8	1.7	1.7
8.0 - 10.0	6.0	9.4	9.1	10.3	10.3	12.1
10.0 - 12.0	26.0	11.1	23.0	23.0	44.8	56.9
12.0 - 14.0	15.0	13.0	45.0	45.0	25.9	82.8
14.0 - 16.0	7.0	14.8	24.0	24.0	12.1	94.8
16.0 - 18.0	3.0	16.8	30.0	30.0	5.2	100.0

Total number of feet = 58.0

Table 5-5b. Permeability Range, P&U Well No. 4, Mt. Simon Core

POROSITY RANGE	FEET IN RANGE	AVERAGE PERM, MD (GEOM.)	(ARITH)	AVERGE POROSITY (%)	FREQUENCY (%)	CUMULATIVE FREQUENCY (%)
0.625 – 1,.250	1.0	1.2	1.2	9.5	1.7	1.7
1.250 – 2.500	1.0	2.0	2.0	10.8	1.7	3.4
2.500 - 5	7.0	3.3	3.4	10.7	12.1	15.5
5 - 10	6.0	6.7	6.8	9.5	10.3	25.9
10 - 20	15.0	14.0	14.0	12.9	25.9	51.7
20 - 40	13.0	289.0	28.0	12.2	22.4	74.1
40 - 80	13.0	53.0	54.0	12.9	22.4	96.6
80 - 160	2.0	119.0	119.0	13.4	3.4	100.00

Total number of feet = 58.0

Table 5-5c. Storage Capacity, P&U Well No. 4, Mt. Simon Core

POROSITY CUT OFF	FEET LOST	CAPACITY LOST (%)	FEET REMAINING	CAPACITY REMAINING (%)	ARITH MEAN	MEDIAN
0.0	0.0	0.0	58.0	100.0	12.0	11.7
2.0	0.0	0.0	58.0	100.0	12.0	11.7
4.0	1.0	0.5	57.0	99.5	12.2	11.7
6.0	1.0	0.5	57.0	99.5	12.2	11.7
8.0	1.0	0.5	57.0	99.5	12.2	11.7
10.0	7.0	8.6	51.	91.4	12.5	--
12.0	33.0	49.9	25.0	50.1	14.0	--
14.0	48.0	78.0	10.0	22.0	15.4	--
16.0	55.0	92.8	3.0	7.2	16.8	--
18.0	58.0	100.0	0.0	0.0	--	--

Total storage capacity in porosity-feet = 697.9

Table 5-5d. Flow Capacity, P&U Well No. 4, Mt. Simon Core

PERMEABILITY CUT OFF	FEET LOST	CAPACITY LOST (%)	FEET REMAINING	CAPACITY REMAINING (%)	GEOM MEAN	MEDIAN
0.005	0.0	0.0	58.0	100.0	16.98	19.10
0.010	0.0	0.0	58.0	100.0	16.98	19.10
0.020	0.0	0.0	58.0	100.0	16.98	19.10
0.039	0.0	0.0	58.0	100.0	16.98	19.10
0.078	0.0	0.0	58.0	100.0	16.98	19.10
0.156	0.0	0.0	58.0	100.0	16.98	19.10
0.313	0.0	0.0	58.0	100.0	16.98	19.10
0.625	0.0	0.0	58.0	100.0	16.98	19.10
1.250	1.0	0.1	57.0	99.9	17.78	19.54
2.500	2.0	0.2	56.0	99.8	18.49	20.0
5.000	9.0	1.7	49.0	98.3	23.64	24.10
10.000	15.0	4.3	43.0	95.7	28.21	28.28
20.000	30.0	17.6	28.0	82.4	41..54	42.19
40.000	43.0	40.7	15.0	59.3	59.15	--
80.000	56.0	84.9	2.0	15.1	118.85	--
160.000	58.0	100.00	0.0	0.00	--	--

Total flow capacity in millidarcy-feet = 1,576.60

Site-specific core data obtained both historically and through recent core analysis, indicate that the upper Mt. Simon at the P&U facility exhibits a porosity range of 2.2% - 17.9%. Horizontal permeability to air ranges from 0.005 to 183 md. Core data from P&U Well No. 4 is included as Appendix 5-III, and the DOE (2011) Arches Study Report is included in its entirety in Volume 3 of this Petition renewal. Geophysical well logs for P&U Well Nos. 3 and 4 are included in Appendix 5-I.

Local Lithologic Analysis and Reservoir Characteristics

The Mt. Simon has recently been studied as a possible candidate formation for CO_2 injection and results of these analyses also provide information pertinent to fluid injection at the Site. Barnes et al. (2009) evaluated the sedimentary facies, lithology, and petrophysics of the Mt. Simon northwest of Kalamazoo area to further understand porosity and permeability development with respect to CO_2 injection. These authors recognized that the Mt. Simon can be subdivided into three general units: a basal pink-red hematite-stained arkosic unit, central medium-coarse grained quartz sandstone with minor shale/glauconite, and upper transitional calcareous, argillaceous sandstone with fine-grained arkose interbeds that occurs conformably below the Eau Claire. Figure 5.3-5a presents the location of the Mirant No. 1 well which is located in Ottawa County north of the P&U Kalamazoo site. Even though relatively distant (40 to 45 miles), the three Mt. Simon facies presented in this figure are also applicable at the P&U site (see Figure 1-1).

Barnes et al. (2009) state that the well log data show the "middle and upper GR log facies of the Mount Simon Sandstone consist mostly of fine- to medium-grained moderately sorted quartzose sandstone with abundant current-induced sedimentary structures, including planar and cross-bedding and minor, thin shale units". The authors also identified marine fossils and various trace fossils within the units that lead them to conclude that the upper Mt. Simon was deposited in a "shallow subtidal, marine, generally high-energy shelf depositional environment". Barnes et al. (2009) also concluded that sandstones within the middle and lower portions of the Mt. Simon were mineralogically mature quartzose sandstones, with K-feldspar present as thin, fine-grained laminae. Pelletal glauconite (indicating a marine depositional environment), interstitial carbonate, and interstitial clay of probable authigenic origin are also present in minor amounts. The authors also observed that the Mt. Simon may be much thinner and shale-rich in northern and eastern portions of the state; north of P&U in Ottawa County, Barnes et al. (2009) further concluded that the Mt. Simon had an average core porosity of 13.4% and permeability of 238 md.

Barnes et al. (2009) also compared core and log porosities and concluded that typically, conventional core porosity is approximately 3% higher than the measured neutron porosity from geophysical well logs. More importantly, the authors noted a correlation between depth of burial and porosity, which showed that regardless of lithology, Mt. Simon sandstone buried at depths greater than 10,000 feet appear to demonstrate less porosity than sandstones buried at shallower depths (Figure 5.3-6a). The authors report that this occurred due to "a global trend of increased quartz diagenesis and porosity occlusion with depth because of increased burial time and temperature above approximately 75-90 °C….the average depth of the Mount Simon Sandstone versus the average NPHI…supports the dramatic decrease in porosity with depth below approximately…6,500-8,000 feet…in Mount Simon wells in the Michigan Basin". Core porosity and permeability relationships are presented in Figure 5.3-6b (Barnes, et. al 2009).

As a result of core and log analysis Barnes et al. (2009) established a general porosity – permeability relationship described by the following equation:

$$K\ (md) = (5 \times E\text{-}04) \times \acute{\varnothing}^{4.815}$$

Where K= permeability and $\acute{\varnothing}$ = porosity.

The authors cautioned that the relationship was general in nature, primarily because of a relatively low correlation coefficient associated with the porosity-depth relationship (Figures 5.3-6a and 5.3-6b). Based on the relationships shown in Figures 5.3-6a and 5.3-6b, and the cited function, the authors chose a 10% porosity cut-off because "above the proposed 10% effective porosity cutoff [the Mt. Simon has] a calculated pore size greater than 4 microns, and therefore these reservoir rocks are interpreted to be dominated by excellent reservoir-quality macropore systems". The authors used a porosity of 10% to calculate an average 33 md. permeability value for the entire net effective thickness of the Mt. Simon that was later used in their large-scale CO_2 sequestration related calculations. Barnes' analysis was intended to provide estimates of regional/basin scale capacities and did not include observed historic injection behaviors or well-test analyses. Other authors, including Zimmerle (1995), observed that illite in sandstones can create large volumes of microporosity and increase pore tortuosity. Short-term and smaller scale reservoir behavior is generally defined by the dominant permeability layers of a system, but long-term, larger-scale performance can also be affected by induced reservoir pressures caused by injection wherein reservoir behavior is affected by contact with the larger surface areas and rock volumes of relatively lower permeability and porosity units.

Net porosity was conservatively calculated by Barnes et al. (2009) by determining the interval thickness that exhibited log characteristics of greater than 10% porosity, less than 50 API gamma units (i.e. clean sandstone), and a density between 2.3 and 2.8 (to eliminate non-quartzitic sandstone lithologies). The authors believed that these cut-offs eliminate inferred, non-sandstone lithologies and provided an overall conservative estimate of regional CO_2 storage capacity. The foot-porosity calculations used by Barnes et al. (2009) are conservative with respect to the porosity cut-off values because a 10% neutron log porosity cut off translates to an equivalent core porosity of greater than 13%, based upon the general log-core relationship developed by Barnes et al. (2009).

Foot porosity calculations were performed using well logs from P&U Well No. 4 (Table 5-7). Digital LAS files supplied in the appendices to this section, were analyzed using PETRA software to derive effective thicknesses for various assumptions regarding property cut-offs. The resulting thicknesses determined for these log cut-offs are presented in the following table.

Table 5-7. Effective Thickness of the Mt. Simon Sandstone in the Kalamazoo Area, Well No. 4

Interval	Depth (ft)	Formation Thickness (ft)	Ft. Por >8% Neutron	Ft. Por >8% Density	Ft. Por >8% Neutron	Ft. Por >8% Density	Ft. Por >10% Neutron	Ft. Por >10% Density	Ft. Por >10% Neutron	Ft. Por >10% Density	AVG Neutron Ø	AVG Density Ø
			API <30	API <30	API <50	API <50	API <30	API <30	API <50	API <50		
By Regulatory Unit												
Trempealeau (Confining Zone)	3992-4254	262	23.5	3	27.5	4	9.5	2.5	11.5	3.5	0.04	-0.04
Injection Zone	4254-5602	1348	183.5	348	315.5	575.5	80.5	342	145	559	0.1	0.131
Arrestment Interval	4254-4750	496	34.5	62.5	48	82	23	56.5	30	72	0.12	0.111
Injection Interval	4750-5602	852	149	285.5	267.5	493.5	57.5	285.5	115	487	0.1	0.143
By Geologic Formation												
Trempealeau	3992-4254	262	23.5	3	27.5	4	9.5	2.5	11.5	3.5	0.04	-0.04
Franconia	4254-4417	163	0	0	5	0	0	0	4	0	0.11	0.071
Galesville/Dresbach	4417-4520	103	34.5	62.5	43	82	23	56.5	26	72	0.09	0.134
Eau Claire Upper	4520-4750	230	0	0	0	0	0	0	0	0	0.15	0.129
Eau Claire Lower	4750-4950	200	0	0	0	0	0	0	0	0	0.12	0.137
Top Mt. Simon	4950-5060	110	1	2.5	34	65.5	0	2.5	12	65.5	0.09	0.155
Middle Mt. Simon	5060-5162	102	25.5	41.5	63.5	92.5	13.5	41.5	30.5	92.5	0.09	0.157
Lower Mt. Simon	5060-5467	407	146.5	280	198	378.5	56.5	280	82	372.5	0.08	0.141
Total Mt. Simon	5467-5602	135	1.5	3	36	50	1	3	21	49.5	0.11	0.149
	4950-5602	652	149	285.5	267.5	493.5	57.5	285.5	115	487	0.09	0.145

As shown in this table, assuming the most conservative cut-off of greater than 10% porosity and less than 50 API units, the effective Mt. Simon thickness varies from 115 to 487 feet depending on the porosity tool. Based on review of local log lithology responses and the fact that 8% log porosity is equivalent to 11% core porosity, a more realistic range of effective thickness is based on cut-offs of 8% and 30-50 API units. This analysis yields a range of effective Mt. Simon thickness of about 285 feet to 493 feet.

Eau Claire Formation (Injection Interval and Arrestment Interval)

The lower portion of the Eau Claire is included in the injection interval in both the permit and approved petition. Regionally, the Eau Claire is highly variable from a compositional standpoint, consisting of fine grained sandstone with dolomitic cement in its lower half and siltstones, shales, and sandstone in the upper half. The entire thickness is glauconitic. The Eau Claire thickens to over 800 feet toward the center of the Michigan Basin (Figure 5.2-9a).

The P&U No. 3 lithologic or mudlog description states that the Eau Claire is composed of gray sandstone that is fine grained, glauconitic, and argillaceous; the Formation Description Log also indicates that a dolomite is present in the lower portions of the Eau Claire, which is described as limey and buff colored with fine-grained sandstone and minor amounts of glauconite. Siltstone is also present in the unit, and both siltstone and shales are described as being red or pink in color. The geophysical logs at P&U Well Nos. 3 and 4 indicate that the Eau Claire exhibits a distinct gamma ray response increase (i.e. higher API unit response) from about 4,750 feet to the formation top. Table 5-7 presents the general porosity characteristics of the Eau Claire, and also differentiates between the upper and Lower Eau Claire which is information separated at 4,750 feet because this is the top of the Injection Interval.

The P&U wells were not cored in the Eau Claire. However, regional data are available that provides relevant information. DOE (2011) obtained core from the Midwest #2 well in Lagrange County, Indiana (Table 5-4b and Figure 5.3-5b), which showed the unit as a whole varied from 11.5-12.5% porosity and 55-147 md permeability (horizontal). Additionally, Warner-Lambert Well No. 5 in Ottawa County, Michigan was cored through the Eau Claire. X-ray diffraction was performed on the core. The X-ray diffraction analysis revealed quartz to be the highest percentage of the minerals found in the formation. The bulk percentage of quartz ranged from 35% to 58%. K-Feldspar was the next abundant mineral ranging from 19% to 32%. The third most abundant minerals are dolomite and calcite ranging from 12% to 23%. The core lithology is consistent with local and regional driller's logs that describe the Eau Claire as a sandstone with shales and dolomite. The surface gamma ray log run on the Warner-Lambert Eau Claire core shows the core exhibits natural radiation from 80 API units to almost 160 API units, which is significantly higher than the average API value for the underlying Mt. Simon, and also corresponds to the increasing API content of Eau Claire units upsection. The core gamma ray is consistent with the lithologic description of sandstone with laminated shale beds based on physical samples.

A core flow study was conducted on plugs from two cores taken from the Eau Claire, one upper and one lower, based on samples obtained during the drilling of the Warner-Lambert No. 5 well. Interval data and plug-specific information was obtained. These results are summarized in Tables 5-8a and 5-8b below.

Table 5-8a. Eau Claire Core Data Warner-Lambert Well No. 5

Plug Interval (ft)	Horizontal Plug Porosity	Permeability-Air (md)		Permeability-Fluid (md)	
		Ambient Horizontal	Net Overburden Horizontal	Brine Horizontal	Waste Horizontal
4,912-4,913	0.11	0.744	0.365	2.142×10^{-4}	1.621×10^{-4}
4,918-4,919	0.14	6.747	6.342	2.23	---
4,926-4,927	0.17	1.483	0.968	1.366×10^{-4}	---
4,933-4,934	0.09	4.308	0.338	2.411×10^{-5}	---
4,940-4,941	0.15	1.059	0.324	1.83×10^{-4}	---

Table 5-8b. Core Plug Analyses - Eau Claire Warner-Lambert Well No. 5*

Plug Depth (ft)	Grain Density (g/cm3)	Porosity	Horizontal Permeability (md)		Vertical Permeability (md)	
			Air	Brine	Brine	Injectate
4,912.5	2.689	0.11	0.744	$2.14\text{x}10^{-4}$	---	---
4,913.5	---	---	---	---	$1.4\text{x}10^{-5}$	$1.7\text{x}10^{-5}$
4,918.3	2.657	0.14	6.747	2.23	---	---
4,919.5	---	---	---	---	$3.0\text{x}10^{-3}$	$4.0\text{x}10^{-3}$
4,924.5	---	---	---	---	$2.0\text{x}10^{-3}$	$3.0\text{x}10^{-3}$
4,926.9	2.592	0.17	1.483	$1.366\text{x}10^{-4}$	---	---
4,930.5	---	---	---	---	$<10^{-6}$	$5.2\text{x}10^{-6}$
4,933.3	2.666	0.09	4.308	$2.4\text{x}10^{-5}$	---	---
4,936.5	---	---	---	---	$1.4\text{x}10^{-6}$	$7.0\text{x}10^{-6}$
4,940.7	2.647	0.15	1.059	$1.83\text{x}10^{-4}$	$3.0\text{x}10^{-3}$	$2.0\text{x}10^{-3}$

* Average porosity and permeability values from Envirocorp's Response to Notice of Deficiencies with respect to the Park-Davis Petition, February 28, 1992 indicated an average porosity of 13.2%, average vertical permeability of .0080145 md (brine), and average horizontal permeability of 0.4461152 md (brine).

To summarize, all descriptions indicate that the Eau Claire Formation in the vicinity of Kalamazoo is composed of sandstones with significant quantities of interbedded shale increasing upsection, as verified by log and core response. The unit is relatively porous, but exhibits variable horizontal permeabilities of between $1.366\text{x}10^{-4}$ and $2.411\text{x}10^{-5}$ md, up to 147 md in Indiana core. Vertical permeabilities to brine of between $5.2\text{x}10^{-6}$ and $4.0\text{x}10^{-3}$ md were measured. In a layered shaley and silty unit, effective vertical permeability to brine is typically lower than horizontal permeability and effective permeability across the unit will be dominated by the lowest permeability layer through which flow must occur. The Upper Eau Claire serves as a primary seal (aquiclude) within the Arrestment Interval that will retard vertical fluid migration from the Mt. Simon. Geological literature regarding the Michigan Basin does not indicate the potential for fracturing or faulting of the Eau Claire Arrestment Interval. Detailed local correlations of the well logs available for wells in the area and structure mapping also show no evidence of faulting within the geologic column as a whole in the Kalamazoo area and, specifically, the Eau Claire.

As shown on Figure 5.3-7a and Table 5-3, the Eau Claire is approximately 430 feet thick in the Site area. Figure 5.3-7b is a local structure contour map constructed at the top of the Eau Claire.

Galesville/Dresbach (Arrestment Interval)

The Formation Description Log indicates that the Galesville/Dresbach at P&U Well No. 3 is about 101-103 feet thick at the P&U site, and is composed of medium grained, porous sandstone. It is described as being gray, and alternatively tight and friable or porous, with rare green shale partings near the base. The unit contains no glauconite based on cuttings descriptions. The Galesville/Dresbach was cored in P&U Well No 4 and summary results of core analysis are presented in Table 5-9. Full data concerning the P&U Well No. 3 and 4 cores are presented in Appendix 5-III.

Table 5-9. Summary of Galesville/Dresbach Core Data Results, P&U Well No. 3

Cored Interval (ft depth RKB)	Average Maximum Horizontal Core Permeability over Interval, md	Average Porosity (%)in Interval	Average Vertical Permeability in Interval, md
4,460-4,463	136.1	5.7	<0.1
4,463-4,465	174.5	13.4	87.5
4,465-4,468	2.6	7.1	.27
4,468-4,470	101	11.3	20
4,470-4,472	0.5	4.4	<0.1
4,472-4,473	70	13.1	12
4,473-4,477	<0.1	5.0	0.25
4,477-4,485	29.65	9.0	1.75

Warner-Lambert Well No. 5 in Ottawa County also cored the Galesville/Dresbach. Five core plugs were taken from the Warner-Lambert Well No. 5 Galesville/Dresbach core and X-ray diffraction analysis was performed. The tests showed that the Galesville/Dresbach is sandstone with 72% to 99% of its matrix as quartz with only about 4% of the bulk minerals being calcareous (i.e. probably not cemented with calcite). With no calcite cement, the unit would be uncemented or cemented by silica, and the lack of cement, or absence of cement, is supported by the “no cementing” and friable lithologic description. After quartz, the next most abundant minerals found were the K-Feldspar minerals with calcite and dolomite, consistent with the lithologic description of the core at the depth 4,848.7 feet "sandstone, dark grey, fine grained with slightly calcareous shale laminations." While this core was taken about 40 miles northwest of the P&U site, it does show that the Galesville/Dresbach is composed primarily of sandstone.

A surface gamma was run on the full length of the Galesville/Dresbach core taken from the Warner-Lambert No. 5 well. The Galesville/Dresbach core showed a surface gamma ray curve with relatively low natural radiation ranging from approximately 10 API units to just over 40 API units, consistent with the lithologic descriptions of sandstone with occasional shale laminations and with the geophysical logs run on the open hole during drilling of P&U Well Nos. 3 and 4.

Warner-Lambert Well No. 5 core analyses results, as well as plug sampling results, are presented in Tables 5-10a and 5-10b, below.

Table 5-10a. Galesville/Dresbach Core Data, Warner-Lambert Well No. 5

Plug Interval (ft)	Horizontal Plug Porosity	Permeability-Air (md)		Permeability-Fluid (md)	
		Ambient Horizontal	Net Overburden Horizontal	Brine Horizontal	Waste Horizontal
4,822-4,823	0.11	374.949	155.495	241.764	---
4,829-4,830	0.19	1,818.168	437.111	2,029.131	---
4,837-4,838	0.17	627.395	235.426	562.335	---
4,844-4,845	0.18	760.326	324.910	386.644	---
4,848-4,850.5	0.20	169.010	25.646	115.079	---

Table 5-10b. Galesville/Dresbach Core Plug Analyses Data, Warner-Lambert Well No. 5

Plug Depth (ft)	Grain Density (g/cm^3)	Porosity	Horizontal Permeability (md)	
			Air	Brine
4,822.9	2.666	0.110	374.949	242
4,829.5	2.641	0.190	1,818.168	2,030
4,837.4	2.627	0.170	627.395	562
4,844.0	2.635	0.180	760.326	337
4,848.7	2.600	0.200	169.010	115

Figure 5.3-8a is an isopach map of the Galesville/Dresbach, which shows that the interval is generally 100 feet thick in the Site area. Figure 5.3-8b is a structure contour map constructed at the top of this interval. The formation is not part of the completion in the P&U wells, and serves as a pressure bleed-off zone above the Eau Claire within the Arrestment Interval.

Franconia (Arrestment Interval)

The Franconia was identified in P&U Formation Description and Drillers Description/strip log for Well No. 3. In this log, the Franconia is described as primarily a sandstone unit that is fine grained with carbonate cement and "heavy with" glauconite. Sandstones are medium to fine grained. This description is consistent with well log data which shows high gamma ray response throughout the interval. As shown in Figure 5.2-11, the unit is approximately 163-175 feet thick at the site, and occurs at a depth of approximately 4,254 feet RKB. Table 5-7 presents calculated porosity values for the interval based on the Well No. 4 log using the PETRA well log analysis program. Log data show that the Franconia porosity varies from 0 to over 20%, with porosity occurring as variably cemented intervals in the unit. The Franconia is described elsewhere as containing more dolomitic and shale-rich sections; for example, at the Warner-Lambert Well No. 3 in Ottawa County, the Franconia is described as being approximately 117 feet thick and composed of buff colored dolomite with fine grained sandstones that are glauconitic with red and grey shale. Similarly, the Franconia at Warner-Lambert Well No. 4 is described as a 112 feet thick interval composed of sandstone that is fine grained, gray to red in color, with glauconite and green shale as well as dolomite. At Warner-Lambert Well No. 5 the driller's log description indicates that the Franconia is about 109 feet thick and is composed of interbedded sandstones and dolomites, with sandstones occurring at the base of the unit. Sandstones are described as light grey to buff in color, fine to medium grand with glauconite and dolomitic and siliceous cement. Dolomites are described as tan to light brown and light grey, fine to very finely crystalline with some sucrosic intervals. Glauconite may be present in dolomites, and green-grey shaley intervals are described.

Figure 5.3-9a is an isopach of the Franconia in the Site area. This map indicates the Franconia varies from about 163 to 175 feet thick. Figure 5.3-9b is a local structure contour map constructed at the top of the Franconia.

5.3.2.3 Ordovician Trempealeau Formation (Confining Zone)

In contrast to the deeper Cambrian units and the Injection Interval, units within the Ordovician are composed predominantly of carbonates, indicative of changes in the regional depositional systems. Of these, the basal Ordovician Trempealeau Formation is the Confining Zone as identified in both the P&U well permits and petition.

The Well No. 3 driller's log describes the Trempealeau as a thick, dense dolomite that is white with minor amounts of pyrite and gray shale. The Trempealeau is also limey at the base with interbedded fine-grained sandstone. Glauconite and pyrite occur throughout the unit. The Trempealeau is 252-262 feet thick at the site, and occurs approximately 4,000 feet RKB. Table 5-7 presents the PETRA calculated median porosity for the unit, showing that the interval exhibits an average porosity of less than 4%.

The local characteristics of the Trempealeau are verified by descriptions in the region, supporting both the lateral continuity of the Confining Zone and consistent low permeability and porosity characteristics. At the BASF No. 1 well in Ottawa County (T5N, R15W, Section 30), the Trempealeau is described as dolomite that is sandy at the base, with decreasing sand percentage upsection. The dolomites are light tan to tan and grey in color, with red/pink coloration and varying intercrystalline porosity. The units are variably described as fine to medium grained (sucrose to micritic), and may contain shale that is present in traces. Glauconite is also present. The Trempealeau is approximately 218 feet thick at the BASF No. 1 well. The Trempealeau is about 215 feet thick at BASF No. 2, and is reported to be composed entirely of dolomite at this location. The dolomite is described as white to tan and light grey, fine grained to very finely crystalline and sandy with some oolitic chert and traces of glauconite. A "slight red staining that gradually increases with depth" was observed. At BASF No. 3, no lithologic descriptions were presented for the formation in available data, and it appears to be about 218 feet thick based on well log data.

The Trempealeau is described as a 211 foot-thick dolomite and sandstone unit in at the Heinz No. 1 well location in Ottawa County (T5N, R15W, Section 30). The dolomite is white to light tan and fine grained to granular, with sandstone described as white, quartzitic, and fine to medium grained. Sandstone percentage increases toward the base of the unit. The Heinz No. 2 well data suggest that the Trempealeau is about 217 feet thick at this location; no lithologic descriptions were included in the available data. The Trempealeau is about 210 feet thick at the Heinz No. 3 well location, and is described as an arenaceous dolomite that is light tan, white and/or grey with fine to medium crystallinity with oolitic chert and glauconite.

At the Warner-Lambert No. 3 well in Ottawa County, the Trempealeau is described as a 203 foot thick dolomite that is white with minor amounts of buff dolomite and gray and red shale. Lower portions are described as containing green glauconite and pink staining. The Trempealeau is about 207 feet thick at the Warner-Lambert No. 4 location, and is described on the Lithologic Description Log as being a dolomite that is white and limey with scattered sand grains. The mudlog for Warner-Lambert No. 5 indicates that the Trempealeau is about 207 feet thick and is composed of arenaceous dolomite that is white, brown and/or tan in color (to light buff) that is of varying crystallinity (very finely crystalline to microcrystalline), and also contains shale and oolitic chert.

Figure 5.3-10a presents an isopach of the Trempealeau and shows that the unit has very little isopach variation in the Site area. Figure 5.3-10b is a structure contour constructed at the top of the Trempealeau in the Site area.

5.3.2.4 Units Above the Confining Zone (Ordovician- Mississippian Units)

Several Ordovician, Devonian and Mississippian-aged units occur above the Trempealeau as discussed in Section 5.2.3 of this document. The units include the Prairie du Chien, Black River Group, Trenton, Utica Shale, Manitoulin Dolomite, Cabot Head Shale, Niagara Group, Salina Group, Bass Island Group, Detroit River Group, Traverse Group, Antrim Shale, Ellsworth Shale, and the Coldwater Shale. In total, this interval is approximately 3,622-3,672 feet thick at the Site.

Figure 5.3-1a shows the location of non-freshwater wells within two miles of the Site. Besides Well Nos. 3 and 4, there are only three other wells within the two mile area; none penetrate the Confining Zone. No well logs are available from the MDEQ database for these wells, and all three were plugged and abandoned between 1945 and 1984. As discussed further in Chapter 9, the wells were completed to depths of 1,532 feet (Well No. 1), 1,476 (Well No. 2), and 1,294 (Deright #1) feet below ground surface. Well Nos. 1 and 2 were drilled to the Detroit River/Dundee, while the Deright #1 was drilled to the Traverse limestone. It is assumed that the target intervals exhibit porosity and permeability consistent with regional data, and also exhibit natural brine concentrations in excess of 100,000 mg/l. They provide evidence of another permeable bleed-off zone between the base of the lowermost USDW and the top of the Injection Interval. This variation in vertical and horizontal rock properties satisfies hazardous waste well siting criteria and provides an additional level of protection for isolating Mt. Simon injection activities from useable groundwater. In summary, little geologic information is available from these wells and none of the wells penetrated the geologic column of primary interest including the Confining Zone and therefore not considered further in this document.

5.3.2.5 Glacial Drift

Unconsolidated material of various origins and characteristics are present in the Kalamazoo area. Figure 4-4 is surficial geologic map of the Kalamazoo area. See Section 4.0 for detailed discussion of the Glacial Drift geology. Also see Section 5.3.3, below for local hydrologic information including that of the glacial drift.

5.3.3 Local Hydrology

As indicated previously in Section 4.3, glacially-sourced sediments account for all of the geologic column between ground surface and subcropping bedrock units. In summary, there are several different glacial units in the Kalamazoo area that occur at and around the P&U site (Deutsch, 1960, Rheaume, 1990). Wisconsin-age glaciation in Kalamazoo County consisted of two large ice lobes, the Saginaw lobe moving from the east side of the state and the Michigan lobe from the west side, preceding an ice sheet. Melting of these lobes and deposition of entrained sediment therein formed the glacial landforms characteristic of Kalamazoo County. Deposits include till plains, Tekonsha Moraine, the Climax-Scott Outwash Plain, and the Galesburg-Vicksburg Outwash Plain. Additionally, numerous kettle lakes occur in the area. Melting of the glacial lobe resulted in glacial retreat and formation of down-cut glacial-drainage channels of the present-day Kalamazoo River valley. Rheaume (1990) states “Eventually the ice lobes retreated out of Kalamazoo County, and new drainage channels were opened, directing meltwater away from the area. When this glacial drainage changed, the large discharge of the glacial Kalamazoo River was reduced substantially to its present size.” As shown in Figure 4-4, the P&U site is underlain by the Galesburg-Vicksburg outwash plain. Surface geologic units shown in this figure are described as follows:

- Outwash Plain: medium to very coarse sand and gravel; pebbles and conglomerates common
- Upland Moraine and kames fields: mostly sandy till, with boulders and cobbles common at ground surface

- Downcut glacial drainage channels: predominantly medium to very coarse sand and gravel
- Till Plain: predominantly coarse sandy and cobbly till that is clay-rich in areas. Boulders at ground surface.

The USGS drilled several borings in Kalamazoo County that provided a detailed description of glacial geologic units in the area. Almost ubiquitously, glacial units are described as being predominantly sand and gravel, within minimal interbedded clays (Rheume, 1990).

Rheaume (1990) states: "Glacial deposits, consisting largely of sands and gravels, are the source of most ground-water supplies in Kalamazoo County. Data collected for this report indicate that these deposits vary in thickness and permeability, but all deposits can at least produce sufficient supply for domestic use. Aquifers underlying the outwash plains and the downcut glacial drainage channels, which together cover about two-thirds of the county, are the most productive ….[there is] an upper unconfined aquifer throughout almost the entire county and a lower semiconfined aquifer in about one-third of the county. At many locations, the hydraulic connection between the upper and lower aquifers is good enough that, under pumping stress, water will move readily between aquifers." The Kalamazoo-Portage reservoir is described by Rheaume (1990) as presented in Table 5-11.

Table 5-11. Groundwater Reservoir Description, P&U Site Area

Groundwater Reservoir Name	Description	Transmissivity [(gal/d)/ft]	Estimated limits of Development (Mgal/day), 1990
Kalamazoo-Portage	Underlies part of the cities of Kalamazoo and Portage. Upper unconfined aquifer from 0 to 60 ft thick. Transmissivity ranges from 10,000 to 100,000 gal/pd/ft. The lower Kalamazoo-Portage reservoir connects with eh lower Schoolcraft reservoir to the south, the lower Texas reservoir to the west and the upper Kalamazoo River reservoir to the north	10,000-160,000	24 million gallons/day estimated withdrawal rate for a 180 day period without recharge

Rheaume (1990) concludes the following:

> "Thick, glacial sand and gravel deposits provide most ground-water supplies in Kalamazoo County. These deposits range in thickness from 50 to about 600 feet in areas that overlie buried bedrock valleys. Most domestic wells completed at depths of less than 75 feet in the sands and gravels yield adequate water supplies. Most industry, public supply, and irrigation wells completed at depths of 100 to 200 feet yield 1,000 gallons per minute or more. The outwash plains include the most productive of the glacial aquifers in the county. The Coldwater Shale of Mississippian age, which underlies the glacial deposits in most of the county, usually yields only small amounts of largely mineralized water."

5.3.3.1 Bedrock Aquifers – P&U Area

Bedrock geology of the Kalamazoo area is shown in Figure 5.2-1b. Deutsch et al. (1960) glacial drift is underlain by a "thick sequence of shale, limestone, dolomite, sandstone, and other consolidated sedimentary rocks…. None of these rock formations are known to supply fresh water to wells in the Kalamazoo area." The Coldwater shale is the uppermost bedrock formation under the P&U site and is composed primarily of dark-blue and relatively impermeable shale. While it may locally contain sandstone bearing intervals, no groundwater wells produce from the Coldwater Shale in the P&U area. As discussed in Section 4, P&U monitors groundwater at the facility as part of its RCRA program. Additional discussion of these units is presented in Section 4.3.3.

5.3.4 Local Mineral Resources

No mineral or petroleum resources of any economic value are currently known to be present within the injection or Confining Zones within the AOR. Oil and Gas well field location maps show no major fields in the Kalamazoo county, and all shallow wells that produced in the past being plugged and abandoned. Well lease maps show all posted leases to be inactive (http://www.fetchgis.com/portageweb/rma/PortageMapViewer.html#). Oil and gas reserves are present in units overlying the injection and Confining Zones to the north of the site, but no producing wells were identified within the AOR. According to MDEQ online data, the closest producing well occurs in the Traverse Formation, and is located approximately 22.75 miles northeast of the P&U facility. This well (API 21015192070000) produces oil and is in Barry County (T01N, R09W, Section 12).

5.3.5 Local Seismic Activity

The P&U site occurs in a region where only minor seismic activity has taken place (USGS, 2014) A local seismic risk map (Figure 5.3-11) and regional seismic acceleration map show that the P&U site occurs in an area of both low seismic risk and low peak ground acceleration.

Historic data from USGS suggest that earthquakes have been felt in the region since 1881, but none of these epicentered within 30 miles of the P&U site. Table 5-12 shows the location where Michigan earthquakes occurred since 1887 – 1994 (USGS, and Bricker, 1977). Table 5-12 is based on various references and is intended to show general location and identification of recorded earthquakes and may not be complete. Figure 5.3-12 shows the location of the strongest felt, recorded earthquake in Michigan, which took place in 1947 more than 35 miles southeast of Kalamazoo. The epicenter of that event was actually in Indiana, with a recorded 4.6 magnitude in Michigan (USGS, 2014).

More recent USGS (2014) data suggest at least two earthquakes epicentered in the region since 1994. A small earthquake was epicentered in Indiana about 15 miles south of Sturgis, Michigan (over 50 miles from Kalamazoo), and occurred two years ago (magnitude 3.0). Also, another small earthquake occurred 19 years ago near Waverly, Michigan (also 3.0 magnitude), about 450 miles from Kalamazoo. While not identified on the USGS website, local Kalamazoo newspapers indicate that an earthquake was felt in the Kalamazoo area in 1987, but the epicenter was not identified and no local earthquake was identified in scientific data.

Table 5-12. Michigan Earthquakes within 150 miles of P&U 1872 – 1994

Year	Month	Day	North Latitude	West Latitude	Intensity (Mercalli)	Approximate Radial Distance from P&U (Miles)
1872	02	02	43.6	-83.9	IV	131
1876	01	27	41.8	-84.05	No Data	81
1876	02	27	42.36	-82.83	No Data	140
1887	08	17	42.36	83.16	IV	123
1881	04	20	41.6	-85.8	IV	44
1883	02	04	42.3	-85.6	No Data	26
1897	10	31	41.8	-86.3	No Data	45
1899	10	11	421.	-86.5	IV	51
1899	10	12	42.6	-87.8	III	118
1905	03	13	41.13	-87.6	V	132
1906	04	22	43.1	-87.9	III	134
1906	04	24	43.0	-87.9	III	131
1906	05	19	42.9	-85.7	III	51
1907	01	10	45.13	-86.33	V	205
1918	02	22	42.8	-84.2	IV	80
1925	03	03	42.1	-87.7	II	110
1938	02	12	41.6	-87.0	V	85
1938	03	13	42.36	-82.83	IV	140
1947	05	06	43.0	-87.9	V	131
1947	08	10	41.9	-85.0	VI	37
1956	07	18	43.6	-87.7	IV	145
1956	10	13	42.9	-87.9	IV	128
1967	02	02	42.7	-84.6	IV	62
1981	01	09	43.1	-87.9	II	134
1994	09	02	42.8	-84.6	IV	64

* From Bicker, 1997 and USGS, 2014

Available data indicates that recorded earthquakes in Michigan have typically been mild and epicentered far outside of the AOR. None of the historically reported earthquakes were of sufficient intensity to cause damage to any surface or subsurface structures at the facility. It should be noted that the USGS seismic monitoring system is sensitive enough in southwest Michigan to detect earthquakes down to a magnitude of less than 1 as indicated on the

USGS's real-time earthquake monitoring website (http://earthquake.usgs.gov/earthquakes/recenteqsus). Table 5.15b, prepared by the USGS and presented below, compares magnitude and intensity:

Table 5-13. Earthquake Magnitude vs. Intensity Comparison

Magnitude	Typical Maximum Modified Mercalli Intensity
1.0 – 3.0	I
3.0 – 3.9	II – III
4.0 – 4.9	IV – V
5.0 – 5.9	VI – VII
6.0 – 6.9	VII – IX
7.0 and higher	VIII or higher

(Source: http://earthquake.usgs.gov/learn/topics/mag_vs_int.php)

It is noted that injection-induced earthquakes have occurred infrequently in other areas of the country. Fluid injection-induced earthquakes are typically attributed to increased pore pressure from injection operations, reducing frictional resistance to failure. No induced earthquakes have been known to occur in Michigan. In cases where injection is thought to have caused seismicity, significant injection pressures have often been involved and earthquakes have typically been detected in relatively close proximity to the wellbores (Seeber et al. 2004; Wesson and Nicholson, 1987). However, no earthquakes with epicenters within 30 miles of P&U Well Nos. 3 and 4 have occurred, and injection pressure and volume is strictly limited by permit and continuously monitored since injection into these wells began in 1977. Therefore, there is no evidence to indicate that any injection-induced seismic activity has or will occur in the P&U area.

Based on historic observations, the probability of an earthquake caused by natural forces or fluid injection near P&U is remote. P&U injection activities take place at relatively low pressure into deep, high-porosity sandstones, in an area not subject to any significant earthquake activity. Therefore, the probability of an earthquake of sufficient intensity to damage the injection system, injection well, or the confining layer is very low.

5.4 REGIONAL AND LOCAL GEOLOGY: REGULATORY ANALYSIS AND CONCLUSION

As indicated previously, *40 CFR §* 146.2 specifies the minimum geologic criteria for siting of hazardous waste injection wells, including provision of data to support the geologic suitability of the site such as the thickness, porosity, permeability and extent/continuity of the Injection Zone and Confining Zone, as well as the hydraulic gradients and pressures associated with the Injection Zone. Further, the geologic suitability should be based on an analysis of the stratigraphy, structure, hydrogeology and seismicity of the area, as well as rock properties, aquifer hydrodynamics, and mineral resources. This information is required to demonstrate that the geology of the area can be sufficiently described so that waste fate and transport can be accurately modeled.

Further, *40 CFR §* 146.62(c) states that the wells must be sited in areas as where the Injection Zone has sufficient permeability, porosity, thickness and areal extent to prevent migration of fluids into USDWs, and the Confining Zone must be laterally continuous and free of transecting transmissive faults or fractures over an area sufficient to prevent the movement of fluids into a USDW, with at least one formation of sufficient thickness and with lithologic characteristics capable of preventing vertical propagation of fractures.

Regulations at *40 CFR §* 146.62(e) require that the owner/operator demonstrate that the Confining Zone is separated from the base of the USDW by at least one sequence of permeable and less permeable strata to prevent vertical fluid movement if a transmissive borehole or fault were present in the area, or must alternatively demonstrate that there is no USDW or that the potentiometric surface is sufficient to mitigate upward fluid migration.

Regional geology, including stratigraphy, structures, seismicity, rock properties, hydrology (including hydraulic gradients/pressures), and unit extent and continuity are addressed in Section 5.2. Local analyses of the same properties are presented in Section 5.3. Dozens of figures and tables are included to address these technical issues, and clearly demonstrate that the geologic characteristics of the site are sufficiently and completely described to facilitate accurate waste fate and transport modeling. In sum, all of the information presented in Sections 5.2 and 5.3 clearly show the significant amount of information pertaining to local and regional geology/hydrology that is available, and shows that the Injection and Confining Zones are of adequate thickness and lateral extent to meet the applicable regulatory standards. Additional information pertaining to characteristics of the injection and Confining Zone is presented in Section 5.5, below.

5.5 REQUIREMENTS OF THE INJECTION AND CONFINING ZONES

As indicated above, strata in the P&U area are well studied by P&U, its consultants and other authors, and show that Injection Zone and Confining Zones are thick, well defined, and laterally continuous. *40 CFR §* 146.62(b) requires that geologic suitability of the site must be established based on an analysis of the structural and stratigraphic geology, as well as the hydrogeology, and the seismicity of the region. Further, detailed information pertaining to rock properties and aquifer hydrodynamics must be provided, as well as mineral resources. All of this information must be provided to determine the geologic suitability of the site for waste injection. Sections 5.1-5.4 above, address these requirements.

Based on the information established in Sections 5.1-5.4, Sections 5.5.1 and 5.5.2, the following summarizes information supporting the suitability of both the Injection and Confining Zone for waste disposal as required in 40 *CFR §* 146.62(c). Specifically, Sections 5.5.1 and 5.5.2 draw together information presented in previous sections and presents additional analyses to demonstrate that the Injection Zone has sufficient permeability, porosity, thickness and areal extent to prevent migration of fluids into USDWs. Further, these sections address characteristics of the Confining Zone, demonstrating that the zone is laterally continuous, free of transecting transmissive faults or fractures (Sections 5.2 and 5.3) and contains at least one formation of sufficient thickness and with lithologic characteristics capable of preventing vertical propagation of fractures.

5.5.1 Local Geology - Injection Zone

The Injection Zone at the Site consists of the Mt. Simon, Eau Claire, Galesville/Dresbach, and Franconia. The Injection Zone is divided into the Injection Interval composed of the Lower Eau Claire (below 4,750 feet) and underlying Mt. Simon. The Arrestment interval is composed of the Upper Eau Claire, Galesville/Dresbach, and Franconia. All depth units are relative to RKB at P&U Well No. 4, unless specified otherwise.

Properties of the Injection Interval (4,750 feet – Approximately 5,600 feet)

The Mt. Simon Member occurs at a depth of about 4,950 feet RKB at P&U Well No. 4, and is approximately 650 feet thick at the Site. The Mt. Simon is the lowest member of the Munising Formation. Site core obtained from P&U Well No. 4 and mud log descriptions from P&U Well No. 3 indicate that the Mt. Simon is a fine to medium grained, well sorted, silica cemented sandstone. A lithologic description of the full length of core (5,200 feet to 5,231 feet) taken from the Mt. Simon formation to the north during drilling of Warner-Lambert Well No. 5 verifies that the Mt. Simon is a "very fine grey sandstone with occasional shale lamination".

As presented in Sections 5.2 and 5.3, the Mt. Simon is thick, laterally continuous sandstone with defined lithologic characteristics. Figures 5.2-3, 5.2-4, 5.2-8a, 5.2-8b, 5.3-2, 5.3-3, 5.3-4a and 5.3-4d demonstrate the lateral continuity of the unit, as well as overall unit thickness. Recent work by Barnes et al. (2009) indicate that the interval exhibits three distinct zones (Table 5-14).

Table 5-14. Interpreted Physical Properties, Select Geologic Units, using PETRA Well Log Analysis

Formation	Average Density Porosity	Average Neutron Porosity	Average PHIA Porosity	Average Density	Average Gamma Ray
Detroit River Group	0.064	0.099	0.088	2.608	18
Bass Island Group	-0.024	0.107	0.041	2.749	31
Salina Group	-0.018	0.092	0.037	2.739	37
Niagara Group	-0.002	0.118	0.058	2.713	11
Cabot Head Shale	0.077	0.215	0.146	2.587	70
Manitoulin Dolomite	-0.017	0.147	0.065	2.738	53
Utica Shale	0.384*	0.324*	0.353*	2.092	98
Trenton	-0.013	0.005	-0.004	2.732	19
Black River Group	0.001	-0.004	-0.002	2.708	16
Prairie Du Chien	-0.011	0.054	0.022	2.728	34
Trempealeau	-0.035	0.038	0.001	2.767	19
Franconia	0.071	0.106	0.088	2.596	88
Galesville/Dresbach	0.134	0.086	0.11	2.495	25
Eau Claire Upper	0.129*	0.145*	0.137*	2.503	125
Eau Claire Lower	0.137*	0.118*	0.127*	2.49	107
Mt Simon Upper	0.155	0.089	0.122	2.46	51
Mt Simon Middle	0.157	0.091	0.124	2.458	35
Mt Simon Lower	0.149	0.107	0.128	2.471	71
Mt Simon (total)	0.145	0.088	0.117	2.476	40

*Porosity reflects high shale content

Table 5-14 indicates that the Mt. Simon includes at least the three zones presented by Barnes et al. 2009. The geologic discussion within the previous petition made no mention of layering within the Mt. Simon, and the most recent permit application for Well Nos. 3 and 4 only states the following:

> "The Mt. Simon in the area of the facility is described as a medium to coarse-grained, moderately sorted quartz sandstone. There are small amounts of shale and sandy dolomite in the upper portion of the formation. The lower portion of the formation is somewhat arkosic, particularly in southwestern Michigan. The Mt. Simon is about 600 feet thick at the P&U facility thickening towards the center of the Michigan Basin as indicated on Figure F-12."

As shown in Table 5-14 and Figure 1-1, the upper and lower Mt. Simon are characterized by relatively higher overall gamma ray response is comparable (12.2%-12.8% average), but these values are affected by the presence of shale in the upper and lower intervals.

The Eau Claire Member conformably overlies the Mt. Simon with a transitional contact between the two units. The lower portion of the Eau Claire (4,780 to 4,950 feet RKB in Well No. 4) is included in the injection interval. As shown by local logs and discussed above, this portion of the formation is composed of interbedded shales and sandstones that are medium to coarse grained with glauconite. Average porosity of the Lower Eau Claire, as shown in Table 5-14, is 12.7%.

Properties of the Arrestment Interval

<u>Upper Eau Claire Member (4,520-4,750 feet)</u>

Driller's logs for Well No. 3 document that unit contains silt/sandstone and shale, with a distinct increase in the shale and glauconite content in the Upper Eau Claire, as evidenced on local well logs. No local core was available, but the Warner-Lambert Well No. 5 in Ottawa County was cored over a 25 foot section of the Eau Claire (4,912 feet to 4,941.3 feet), that corresponds to the Upper Eau Claire at the P&U site. This Eau Claire core is described as a "sandstone, brown to black, fine grained slightly calcareous cementing with reddish brown shale lamination." The description of the Eau Claire is fairly consistent throughout the length of the core. Table 5-14 presents average porosity from 12.9 - 14.5%.

Table 5-8b shows vertical brine permeability of the Upper Eau Claire can vary between 3.0×10^{-3} and $<10^{-6}$ md (injectate) based on data from the Warner-Lambert Well No.5 in the Holland, Michigan area approximately 40 miles to the northwest. These values are useful for assessing the low vertical permeability of the Upper Eau Claire.

Galesville/Dresbach Member (4,417- 4,520 feet)

The Galesville/Dresbach overlies the Eau Claire. The P&U Well No. 3 driller's log indicates that the Galesville/Dresbach is composed of gray sandstone that varies from tightly cemented to friable zones. Core data summarized in Table 5.9 indicates that the porosity varied from 4.4%-13.4%, horizontal permeability samples ranged from <0.1 to 174.5 md, and the vertical permeability samples ranged from <0.1 to 87.5 md. The previous application and permits did not address this interval in any detail, so additional analysis was performed using PETRA and the Well No. 4 log to determine interval porosity based on log response. These results are summarized in Table 5-14, and show the average log-based porosity to be 11%.

These data indicate that the Galesville/Dresbach contains relatively porous sandstone intervals, with lower portions exhibiting shale-rich sequences that offer low vertical permeability. The Galesville/Dresbach would serve a pressure bleed-off zone within the arrestment interval.

Franconia Member (4,254- 4,417 feet)

Overlying the Galesville/Dresbach is the Franconia Member. Cutting logs from the P&U well No. 3 describe the Franconia Member as a glauconite-rich sandstone, with upper intervals containing interbedded dolomite. Table 5-14 presents interpreted density and porosity of individual beds within the Franconia, including gamma ray response and computer-picked averaged porosity. The average log-based porosity is 9%. Gamma ray response reflects the presence of both shale and glauconite in the Franconia. Shale intervals serve as impediments to vertical fluid movement.

5.5.2 Local Geology - Confining Zone

Trempealeau Formation (3,992 – 4,254 feet)

The cutting logs from Well No. 3 describe the Trempealeau as a white to off white dolomite with minor pyrite and shale. More detailed descriptions from the Ottawa wells state the interval is fine to medium grained, crystalline, arenaceous, dolomite, to white orthoquartzite and oolitic chert. This unit serves as an aquiclude (confining unit) and is about 250 feet thick at the P&U site.

Table 5-14 presents log-based porosity of the Trempealeau as encountered in P&U No. 4. These data indicate that the average porosity is less than 1%, and the unit exhibits low shale content, verifying log data and the viability of the unit as the Confining Zone. The unit is thick and ubiquitous through the region, further validity this section as the Confining Zone.

5.5.3 Properties of the Overlying Units

Ordovician Units

Prairie du Chien Group (3,596-3,992 feet)

The Prairie du Chien unconformably overlies the Trempealeau formation. It consists of white dolomite with varying amounts of gray shale and poorly sorted quartz sandstone. Table 5-14 presents log interpreted porosity and gamma ray characteristics of the Prairie du Chien as encountered in P&U No. 4. These data clearly show that the approximately 400 foot thick Prairie du Chien Group exhibits an overall porosity of less than 3%, and serves as an impediment to vertical fluid migration.

Trenton and Black River Groups (3,102 – 3,596 feet)

Trenton and Black River Groups consist of white, gray, and tan to brown limestone and dolomite. The basal unit of the Black River Group is the Glenwood Shale. The Glenwood is a waxy, green to gray, pyritic, and sandy shale. It is interbedded with thin layers of red to dark brown sandy and silty dolomite, dolomitic sandstone and limestone. In most cases, there are abundant quartz grains at the shale-dolomite contacts. Layers of the Group have confinement properties. Table 5-14 presents log-based porosity of the Trenton and Black River Groups.

Utica Shale (2,860-3,102 feet)

The Utica Shale consists of gray blue muddy shale with a minor amount of dolomite at the Site. Based on average porosity values determined by well log analysis from the P&U Well No. 4 (Table 5-14), the Utica Shale has a net shale thickness in the area of review of about 240-250 feet and is laterally pervasive throughout not only the AOR, but the entire Kalamazoo area.

Silurian Units

The Clinton-Cataract Group (2,546-2,820 feet) consists of gray, red and green shale in the upper portion and tan and gray dolomite in the basal portion. The Clinton Cataract, including the Cabot Head Shale and Manitoulin Dolomite, is a secondary confining unit.

Niagara Group (2,201-2,546 feet)

The Niagara Group conformably overlies the Clinton-Cataract Group. The upper portion consists of tan to brown and white to grey dolomite. The lower portion consists of varicolored shale. The Niagaran is a secondary confining unit.

Salina Group (1,795-2,201 feet)

The Salina Group conformably overlies the Niagara Group. It consists of alternating carbonate, shale and evaporite units. The Salina Salt is described as light gray translucent with banding of anhydrite laminae which contain carbonaceous matter and scattered pyrite grains. The combination of carbonate, shale and evaporite units make the Salina an excellent secondary confining unit. Remobilized salt will tend to plug pore spaces in the carbonate units. The Salina is a secondary confining unit.

Bass Island Group (1,750-1,795 feet)

The Bass Island Group conformably overlies the Salina Group. It consists of buff to pink, argillaceous and anhydritic dolomite. The Bass Island Group is a secondary confining unit.

Devonian Units

Detroit River Group (1,508-1,750 feet)

The Detroit River Group unconformably overlies the Bois Blanc Formation. The Detroit River dolomite consists of tan to brown dolomite. The Detroit River Group is both a bleed-off zone and a secondary confining unit. Table 5-14 presents general log characteristics of this interval.

Dundee Limestone (1,450-1,508 feet)

The Dundee Limestone conformably overlies the Detroit River Group. It consists of white to brown limestone. The Dundee is both a bleed-off zone and a secondary confining unit.

Traverse Group (1,203-1,450 feet)

The Traverse Group overlies the Dundee formation. The Traverse consists of white to brown limestone with local porous zones. The Traverse is a secondary confining unit.

Mississippian Unit

Antrim Shale (1,134-1,203 feet)

The Antrim Shale conformably overlies the Traverse Group. At the P&U site, the Antrim is relatively thin (approximately 69 feet). Geophysical log signatures indicate that it has very low permeability. The Antrim is a secondary confining unit.

Ellsworth Shale (765-1,134 feet)

The Ellsworth Shale conformably overlies the Antrim Shale. The Ellsworth is about 370 feet thick at the P&U site and consists of gray-green shale with minor amounts of sandstone and limestone. Geophysical log signatures indicate that it has very low permeability. The Ellsworth is a secondary confining unit.

Coldwater Shale (370-765 feet)

The Coldwater Shale conformably overlies the Ellsworth Shale. It consists primarily of gray shale, micaceous in parts. The Coldwater has confinement properties.

Quaternary Units

Glacial Drift Pleistocene (0-370 feet)

Glacial Drift unconformably overlies the Coldwater Formation. It consists primarily of sand and gravel, with clay intervals. As discussed in Chapter 4, the base of the drift was considered to be the lowest potential Underground Source of Drinking Water (USDW) at P&U. The Glacial Drift is considered an aquifer and is the lower most USDW in the P&U area.

5.6 SUMMARY

*40 CFR §*146.62 specifies minimum geologic criteria for the siting of hazardous waste injection wells, including demonstration of geologic suitability of the site based on the thickness, porosity, permeability and extent/continuity of the Injection Zone and Confining Zone, as well as the hydraulic gradients and pressures associated with the Injection Zone. Data presented in this section indicate that the site satisfies the geologic criteria for siting of hazardous waste injection wells by demonstrating that site stratigraphy, structure, hydrogeology and seismicity of the area meet these standards and criteria. Geologic properties of Injection and Confining Zones are well defined, and aquifer hydrodynamics and mineral resources are addressed. As illustrated by geologic characterization and historic operation of site wells, the Injection Zone has sufficient permeability, porosity, thickness and areal extent to accept injectate and prevent migration of fluids into USDWs. Both the Arrestment Interval of the Injection Zone and the Confining Zone are laterally continuous and free of mappable transecting transmissive faults or fractures within the site area. Further, the Injection Interval is separated from the top of the Confining Zone by sequences of permeable and less permeable strata that prevent vertical fluid movement. The Confining Zone is also separated from the base of the USDW by multiple sequences of permeable and less permeable strata that serve to prevent vertical fluid movement. To conclude, information presented in Sections 5.2, 5.3, 5.4, and 5.5 clearly demonstrate that the Injection and Confining Zones are adequate to meet the regulatory standard.

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